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FEASIBILITY OF THE MILITARY SPACE PLANE
FOR RAPID RESPONSE SURVEILLANCE AND RECONNAISSANCE
SATELLITE CONSTELLATION DEPLOYMENT

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Creative Investigation

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ABSTRACT

As United States' reliance on space systems increases, new means of providing and protecting these systems becomes more critical. The military space plane is one portion of the search for flexible and inexpensive space access, which is the foundation in almost all areas of space activity. This investigation studies the feasibility of the space plane for providing space access for the purposes of national defense, forward presence, surveillance and reconnaissance. It does so by performing an analysis between satellite constellation deployment time and satellite constellation coverage characteristics. First, an analytical coverage analysis on a specific constellation design and the reasoning behind it is provided. From this, general satellite coverage conclusions are drawn which are then verified with simulation software. A timing analysis is then performed taking into account times for launch, plane change, satellite phasing, as well as theoretical MSP turn around. The final results include nine satellite constellation scenarios that provide reasonable coverage characteristics along with their theoretical deployment times. It turns out that the main driving force behind the constellation set up and timing is the latitude of the target location. This latitude dictates the inclination of the orbit, which in turn affects the type of constellation, the number of satellites, as well as the number of SMVs and MSPs. Once these variables are known, timing is calculated based on availability, turn around time, and earth rotation rate.

NOMENCLATURE

MSP – Military Space Plane

SMV – Satellite Maneuver Vehicle

U.S. – United States of America

STK – Satellite Tool Kit

TACSAT – Tactical Satellite

JSTARS – Joint Surveillance and Target Attack Radar System

C3 – Command, Control, and Communications

DoD – Department of Defense

ΔV – Delta Velocity or Change in Velocity

ISP – Specific Impulse

Fps – Feet Per Second

NASA – National Aeronautics and Space Administration

Nm – Nautical Miles

AOP – Argument of Perigee

LAN – Longitude of the Ascending Node

ρ - Earth Angular Radius

R_E – Radius of the Earth

H – Altitude of the Satellite

λ_{max} – Lambda Max

ε_{min} – Minimum Elevation Angle

η_{max} – Maximum Nadir Angle

P – Period of the satellite orbit

FOV – Field Of View

T_{FOV} – Time a ground observer is within the field of view of a satellite

i – Inclination of the satellite orbit plane

ϕ - Latitude

θ_{cov} – Theta Coverage

T_c – Orbit Plane Coverage Time, different from satellite coverage time or FOV

n – Number of Satellites

m – Number of Planes

θ_{nc} – Theta Non-Coverage

T_{nc} – Time of Plane Non-Coverage

T_{gap} – Gap Time or time between satellite field of view

g – Earth's Gravitational Acceleration Constant

m_o – Mass Initial

m_f – Mass Final

R – Ratio of Mass Initial over Mass Final

V_{bo} – Velocity at Burn Out

t_{bo} – Time at Burn Out

h_{bo} – Altitude at Burn Out

β - Azimuth

$\Delta\Omega$ - Change in Longitude of the Ascending Node

INTRODUCTION

Based on the need for low cost, reliable, and rapid space lift (provided in Appendix D), the Military Space Plane (MSP) appears to embody the characteristics that make it stand out as an attractive and viable option for the purposes of providing this very service. Namely the MSP hopes to utilize technologies that promise the potential for successful and reliable space missions. This promise can potentially generate the investment needed to bring about the reduction in costs that are so much desired [1]. Moreover, the specification that the MSP be designed to operate within very short turn around times and high sortie rates provide the possibility that it can be used for rapid reconstitution and deployment of space assets. The combination of space assets that will be studied in this report will include the MSP, the Space Maneuver Vehicle (SMV), and the Tactical Satellite (TACSAT), each of which will be described in more detail later on. Given this combination, the study will present a coverage versus time analysis and discuss the feasibility of using the MSP for reliable and rapid space lift and the potential for assured mission success within the Space Support and Force Enhancement mission elements of the United States Air Force Space Command.

The problem at hand is to determine whether or not the MSP can be used to provide a desired type of coverage in a relatively short amount of time. More specifically, once the target location is known, what type of satellite constellation will provide the desired coverage characteristics such as a minimum gap time or even no gap time at all? Once this is determined, can the constellation be deployed within the time required? In essence then coverage and time become the trade in which case the answer will be determined by the criticality of the situation and the capability of the MSP system to operate within the time frame dictated by the situation. The major assumptions of this study are indicated in the following list:

1. The MSP exists with the capability to provide Single Stage to Orbit as well as Pop-up Mission profiles.
2. The SMV exists with the on-orbit maneuvering capabilities specified within the SMV Technical Requirements Document (TRD).
3. Tactical Satellites will be available in number with modular payload capability such that the payload can be installed at the last minute for the particular mission at hand.
4. The means by which the Tactical Satellite transmits its information has already been determined, established, tested, and accounted for.
5. The initial preparation of the MSP will occur at the onset of heightened tension or hostilities such that at the point of execution, the system is immediately ready for launch.
6. Only one target location will be considered at a time. As such, an entire mission will take place for the sole purpose and desire to gather information about one location.

The method in which I attack this study is threefold. First, an analytical analysis of orbit geometry is performed in order to provide an explanation of general relationships and conclusions with regard to coverage. Second, a satellite simulation software is used to validate the conclusions determined from the analytical analysis. Third, a mission timing analysis is performed based on coverage characteristics and the hypothetical availability of launch assets such as the number of available and orbit capable MSPs.

BACKGROUND

Military Space Plane

The MSP is a launch vehicle that has potentially many advantages over current launch systems such as the space shuttle. The advantageous characteristics that are desired and therefore assumed within this study are that the MSP will:[2]

1. Greatly reduce the cost of placing payloads into orbit
2. Behave like an aircraft and therefore its operations will be compatible with current Air Force operations.
3. Be launch-on-demand with rapid turn around times and high sortie rates.
4. Operate from isolated military bases, most likely from CONUS.
5. Be able to place payloads over any point on the earth within 100 minutes of launch and within 5 hours of notification.

The MSP will be capable of performing two basic types of missions. These missions include the direct orbit mission and the "pop-up" mission. For the direct orbit mission, the MSP will take off, follow a typical launch trajectory very similar to the shuttle launch trajectory, and will then place itself directly into a low earth orbit, most likely a 100 nm circular orbit [2]. Once in orbit, the MSP will be able to deploy SMVs. The SMVs will then have full fuel tanks and full ΔV capability in order to perform constellation construction and tactical satellite deployment.

For pop-up missions, the MSP will not place itself into orbit. Instead, it will pop up the SMV. The SMV will complete the launch sequence by placing itself into a final low earth orbit. A comparison of these two types of missions is provided below in Table 1[3].

	Orbital			Pop-Up		
	East	Polar	West	East	Polar	West
Payload	5-10 Klbs	1-2 Klbs	0 Klbs	40 Klbs	21 Klbs	12 Klbs
Gross Weight	1 – 1.3 Mlbs			1 – 1.3 Mlbs		
Dry Weight	90 – 140 Klbs			90 – 140 Klbs		
Mach Number	25			21 – 23		
ISP	440 Sec			440 Sec		

Table 1. Space Plane Characteristics

From this comparison, it is easy to see that the benefit of the pop-up mission scenario is that the MSP can place more payload into orbit. The table also shows a distinction between Eastern, Polar, and Western launches. This simply has to do with the fact that the earth rotates to the East and is already providing a velocity in the easterly direction. Consequently, for eastern launches the MSP does not have to provide a complete ΔV in order to reach orbit. As a result, more payload can be placed into orbit. The opposite is true for polar and western launches. In these cases the MSP not only has to provide the full ΔV to get into orbit around the earth, but it will also have to overcome the component of velocity provided by the earth in the east direction. As a result, less payload can be placed into orbit for polar and western launches. For this particular study, eastern launches will be assumed. Since most locations that may be potential targets in the

future lie between 50° and -50° latitude, it makes little sense to assume polar or western launches. They simply make life more difficult and expensive.

The issue of both target and launch latitude needs clarification at this point. Given that the maximum latitude that a satellite ground trace will reach will be equal to that orbital inclination, for cases where the target latitude is greater than the launch site latitude it is a simple matter to make up for the difference and launch straight into the proper trajectory and inclination. However, for the case where the latitude of the target is less than the latitude of the launch site, a problem arises. From spherical trigonometry, it can be shown that a launch site cannot launch a satellite directly (without a plane change) into an orbit with an inclination less than the launch site's own latitude. In this case, in order to achieve the correct mission orbit and inclination, the MSP must be launched from a launch site that has a latitude either equal to or less than that of the target. Therefore, if the target latitude is somewhere between -20° and 20° latitude, launch sites outside of the U.S. may be necessary.

Space Maneuver Vehicle

The Space Maneuver Vehicle first came out of a Boeing research effort and eventually found its way into a mini-space plane technology study funded by the U.S. Air Force. The SMV was and is intended to be a payload of the MSP, which is the assumption that will be made throughout this paper [4]. Like the MSP, the SMV is to be reusable and it is to have very rapid turn around times and high sortie rates. As the name implies, the purpose of the SMV is to provide on-orbit maneuvering. Its basic mission is to be launched by the MSP system, get into orbit, deploy payloads, and then reenter the earth's atmosphere and land at a designated base [4]. Again, this can occur in two basic types of missions, either direct orbit insertion or pop-up. If the SMV is placed directly into orbit by the MSP, the SMV will have full fuel tanks and will be

able to perform the maximum ΔV on orbit maneuvering. If the SMV is deployed from the MSP via pop-up, the SMV will have to expend some of its fuel in order to reach orbit. Ultimately this means less on-orbit maneuvering [4].

Once in orbit, the SMV can either perform a mission directly and/or it can deploy payload(s). For this particular study, the SMV will perform the latter mission, deploying tactical satellites. The specifications for the SMV are shown in Table 2 below. The table shows four sizes of the SMV. The Large size is to be considered the nominal size and weight and will be the one considered in this study.

Characteristic	Small	Medium	Large	X-Large
Length	12' – 15'	18' – 22'	24' – 27'	28' – 32'
Gross Weight	4 Klbs	8 Klbs	12 Klbs	16 Klbs
Dry Weight	1 Klbs	1900 lbs	2800 lbs	3700 lbs
Propellant	2600 lbs	5300 lbs	8000 lbs	10,700 lbs
Payload	400 lbs	800 lbs	1200 lbs	1600 lbs

Table 2. ΔV = 10000 – 12000 fps. With auxiliary tanks = 20000 fps

Orbit Scenarios

From the information in Table 2, some potential scenarios for the MSP/SMV combination within the orbital and pop-up mission types can be derived. This will assume a nominal (Large) SMV carrying three 400 lbs TACSATS for a total payload weight of 1200 lbs for the SMV.

- Orbital Mission Type:
  MSP Payload = 12 Klbs
  SMV Gross Weight = 12 Klbs
  Deploy one SMV orbital for one orbit plane and three TACSATS total.

- Pop-Up Mission Type:
  MSP Payload = 40 Klbs
  SMV Gross Weight = 12 Klbs
  Pop-up three SMVs into one plane
  Three SMVs with three TACSATS for nine TACSATS total.

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Given these two scenarios, it can be seen that for direct orbit insertion and one MSP, one orbit plane with three satellites per plane may be achieved. More planes may be achieve by attempting to place each of the three satellites into their own plane, but it will soon be shown that this is very expensive in terms of ΔV. If more planes are desired, more MSPs need to be launched, the number depending on the number of orbit planes desired. For the pop-up scenario, three SMVs are released into the same plane. There are several possibilities in this case. In the first case, one orbital plane with nine satellites may be achieved. In the second case, use the SMV to perform a 120° Longitude of Ascending Node plane change in order to create an evenly spaced symmetrical three plane, three satellites per plane constellation. The ability of the SMV to perform a plane change of this magnitude is questionable and this aspect will be discussed in detail later in the study.

To summarize, this paper will study the use of the MSP/SMV/TACSAT combination. The MSP is expected to support the military vision of Global Engagement. It should be able to cover any point on the earth within hours upon notification, and minutes upon execution [5]. This combination is being studied because it is a requirement that the U.S. maintain the capability to deter threats to the U.S. and allied interest [5]. The MSP/SMV/TACSAT combination can help accomplish the mission by providing reliable space lift, and Force Enhancement through near continuous regional satellite coverage. The MSP will be able to perform direct orbit insertion and pop-up missions. The advantage of direct orbit insertion is that the SMV will have full fuel tanks to do orbit maneuvering, potentially enabling it to build larger satellite constellations. The disadvantage of direct orbit insertion is that the MSP is limited in the amount of payload it can place into orbit. In order to get a full functioning constellation, more MSPs must be launched, which can mean more time and limitations due to launch window

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wait time and set up for the purposes of achieving the correct Longitude of Ascending Node and plane spacing.

Coverage

The primary issue at hand is the issue of coverage versus time. How fast can the military deploy a certain number of satellites in a certain amount of time, and what will the coverage be? On the flip side, given a desired type of coverage, how fast can the military establish that type of coverage and what will it cost in terms of ΔV? Satellite constellation design involves many variables and countless numbers of trades. The aspects that were used in this particular study were the following: [6].

- Establish the Mission Requirements
- Assess specialized orbits
- Deploy single satellite or constellation
- Launch options
- Evaluate growth and replenishment
- Evaluate time and ΔV budget

For this study, the mission requirements are simply to provide the best coverage of one location on the earth's surface and determine how long it takes to achieve that with the MSP/SMV/TACSAT combination and whether or not it really can be done given the ΔV. The question then becomes, what does best coverage mean and what kinds of orbits or constellations can provide this coverage? Given the desire to determine such things as enemy troop movements as well as weapons shipments, weapons supply and configuration, satellites will need to be in an orbit that provides a decent field of view given a particular sensor. It is also necessary to ensure that there are no large gaps of time in which a satellite is not in view of the ground station or target. All of these requirements are affected by variables such as altitude, inclination, eccentricity, number of orbit planes, number of satellites per plane, and even sensor type. The types of orbits that fulfill the variables such that the desired coverage is achieved must be found.

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Typically, the easiest way to conduct constellation design is to start with a circular orbit constellation and then conduct trades on altitude and inclination [6]. For missions considered here it is possible to eliminate a couple of these variables right away. First, inclination can be determined simply because the latitude of the target location is known. For this study, the inclination must be at least as great as the target latitude if not greater. Since most target nations will be within 50° of the equator, inclination will almost always be between 0° and 50°.

The variable of eccentricity brings up the issue of circular versus elliptical orbits. The advantages of circular orbits is that they are easy to create and they can be established directly from launch. Eccentric orbits can also be created directly from launch, but they may be more difficult to maintain and may require more ΔV. Additionally, it is more complicated to perform phasing of satellites within the elliptical orbit because satellite motion is not constant but varies throughout the orbit. As a result of these considerations, circular orbits will be assumed throughout the main analysis of this study. Depending on the results of that analysis, eccentric orbits may or may not need to be analyzed.

Altitude is perhaps the one variable that affects just about everything that can be considered in constellation design. However, in this case certain constraints may help to determine a suitable answer. The one primary constraint is ΔV. Not only must the satellites get placed into orbit, they must also be spread out. Since the pop-up mission type will be used within this analysis, it will be assumed that the MSP will get up to Mach 23 and the SMVs will place themselves into a minimum 300 km nominal parking orbit. If the SMV wants to get higher it will have to use up more ΔV, which means it will further limit its plane change and satellite phasing capability, let alone de-orbit, reentry, and landing. It is also necessary to minimize the time it takes to get a constellation up and running. The higher the altitude chosen, the slower the

satellites will move and the longer it will take to phase them out. As a result of these considerations, the analysis is constrained to an altitude between 300 km and 800 km. At a 300 km altitude the satellites will not remain in orbit as long due to atmospheric drag. However, if the mission dictates that satellites are needed for only one or two months, this altitude may be fine and the ΔV the SMV will need to get to that altitude is no greater than what it will take it to simply reach orbit altitude. At a 800 km altitude the orbit is not so far that huge amounts of ΔV must be used, and the velocity of the satellites is not affected that much, so phasing time can still be relatively small. Also, an 800 km orbit altitude may provide a slightly better field of view than the 300 km orbit and it may also be less susceptible to counter space tactics.

At this point, only two more variables remain, the number of planes and the number of satellites per plane. It is these two variables that the coverage analysis will address. First, it is obvious that the more satellites there are in orbit, the better the coverage. The question is, with a given number of satellites, how many planes provide the best gap time between planes for a particular latitude and inclination, and how many satellites per plane provide the best gap time between satellites? If these two gap times can be minimized, it makes sense that the coverage time can be to achieve the best overall coverage for mission success.

Many of the orbit characteristics that will be used in this study have now been determined and will be summarized. The altitude is going to be between 300 km and 800 km, the eccentricity will be zero, and the inclination will most likely fall between 0° and 50°. For example, if the latitude of the target is 33°, as it is with Iraq, should the inclination be 33°, 35°, or 50°. From the point of view of Δv, it would be desirable to launch into the lowest inclination and utilize as much of the earth's rotation as possible. Additionally, the Military Space Plane Handbook for Wargamers suggests that an "Inclination Equal Target Latitude" orbit can

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potentially provide excellent coverage. For these two reasons, the analysis in this paper will

assume these orbital elements:

1. Semimajor Axis = 6378 km + (300 to 800 km)
2. Eccentricity = 0
3. Inclination = Target Latitude
4. AOP = Not Defined (circular)
5. LAN = Specific definition unnecessary except for relative plane
   spacing

ANALYTICAL COVERAGE ANALYSIS

Before diving into the coverage analysis of the MSP/SMV/TACSAT combination, a few

initial equations and concepts need to be discussed. The first equations that will be necessary for

the analysis are derived from the relationships between the two figures shown below. Figure 1

shows the definition of the angular relationships between a satellite, a target, and the center of

the earth. Figure 2 shows the geometry of a satellite ground track relative to an observer on the

earth's surface.
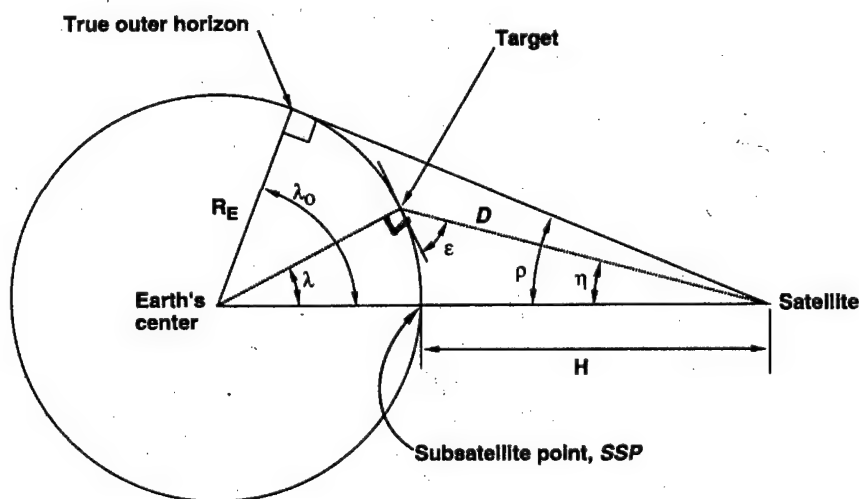
Figure 1. Satellite/Earth Geometry [2]

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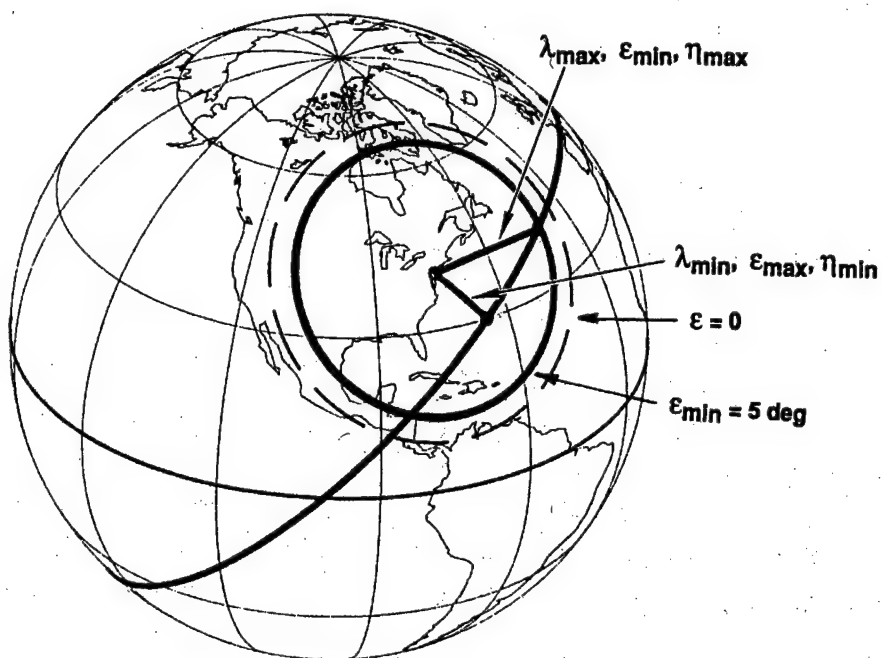
Figure 2. Satellite/Earth Geometry [2]

With the geometry shown in Figure 1 and the nomenclature given in Figure 2, the following

equations can be derived.

$$\sin(\rho) = \frac{R_E}{R_E + H} \tag{1}$$

$$\sin(\eta_{max}) = \sin(\rho)\cos(\varepsilon_{min}) \tag{2}$$

$$\lambda_{max} = 90° - \varepsilon_{min} - \eta_{max} \tag{3}$$

Looking at Figure 2 above, it can be seen that given a value of λ_{max} and a predetermined value of

ε_{min} (which is usually around 5° or 10°), the angular radius of the field of view of the satellite

will be known. This value of λ_{max} is important as it can provide a rough idea of the amount of

time that a particular ground station or location on the earth's surface is in view of the satellite.

Before going any further however, the value of λ_{min} needs to be determined. Without going into

the derivation of the values and again referencing Space Mission Analysis and Design, the necessary values needed are:

$$\text{lat}_{pole} = 90° - \text{inclination} \quad [2] \tag{4}$$

Lat$_{pole}$ is the instantaneous latitude of the orbit pole where the pole is the vector that describes the orbit plane. As such the pole is perpendicular to the orbit plane and parallel to the specific angular momentum vector **h**. Since this study only analyzes the case where the orbit inclination is equal to the latitude of the target country, the latitude of the orbit pole is simply equal to the co-latitude of the ground station. All that remains is the longitude difference between the target country and the orbit pole, or Δlong. Once again, the specific geometry of the orbit results in the very convenient situation where Δlong is always equal to 180°. With this information it is now possible to use the following equation to find λ_{min}:

$$\sin(\lambda_{min}) = \sin(lat_{pole})\sin(lat_{gs}) + \cos(lat_{pole})\cos(lat_{gs})\cos(\Delta long) \quad [2] \tag{5}$$

Finally, the equation for an approximate time that the target location is within the field of view of the satellite is given below:

$$T_{FOV} = \left(\frac{P}{180°}\right)\arccos\left(\frac{\cos(\lambda_{max})}{\cos(\lambda_{min})}\right) \tag{6}$$

In this equation, P is equal to the period of the orbit in seconds. There are a couple of assumptions made in the derivation of this equation. First, the equation assumes a low earth orbit. This means that since the satellite is moving so fast in its orbit in comparison to the earth's rotation rate, from the perspective of the orbiting satellite it would appear that the earth is virtually non-rotating. Second, the equation assumes that the orbit is circular and that the satellite is moving at a constant velocity throughout its orbit around the earth. In both cases, the orbit

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constellations being studied here match these assumptions because they are all low earth orbit constellations and they are all circular with a constant velocity.

At this point the preliminary equations that will be needed for this analysis have been discussed. What will follow is the full analytical derivation of some basic equations that will provide insight into some of the questions about coverage that were brought up earlier. Once again the questions are: how many planes in a constellation provide optimum coverage for a country at a particular latitude and how many satellites per plane will be needed in order to provide a desired gap time between satellites? In order to get a clear picture of what is being derived here, Figure 3 shows the geometry of a hypothetical orbit and target country. In particular, Figure 3 shows the relative geometry between the ground track of the target country as the earth rotates, and the ground trace and the field of view of the satellite as it travels through its orbit. Additionally, Figure 3 shows all the required angles including the inclination of the orbit, the latitude of the target country (ϕ_{gc}), and λ_{max}.
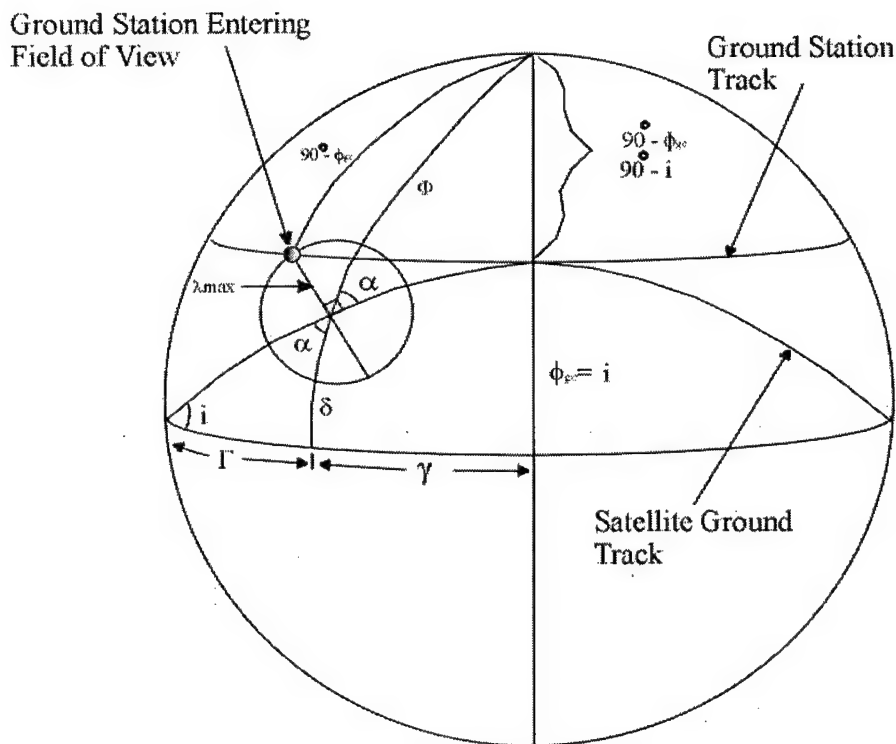
Figure 3. Earth/Satellite Ground Track Geometry

The most important aspect of this illustration of the relative geometry is that it shows the exact

point at which the field of view of the satellite comes into contact with the ground station as the

earth rotates underneath the satellite orbit plane. Given the relationship between the angles

shown, this illustration ultimately reveals **the angle through which the earth rotates while the**

plane is in a position to permit view of the target ground station by the satellite. Moreover,

the total angle through which the earth rotates while the plane of the orbit is in a position to

permit view of the target ground station by a satellite is shown as 2γ. If this angular distance can

be found, it is then possible to know how long the plane will be in a position to allow visibility of

the ground station as well as how long the plane will not be in a position to allow visibility of the

ground station. The goal is to find the angular distance γ, and from there to derive several

relationships that will help answer the questions about coverage.

First, a few basic relationships need to be developed. Notice the spherical triangle in Figure 3 formed by the sides equal to λ_{max}, 90°-i, and Φ, where Φ extends from the top of the earth down to the center of the field of view. Since the inclination of the orbit is equal to the latitude of the ground station the following two equations are true:

$$\phi_{gc} = i \tag{7}$$

$$90° - \phi_{gc} = 90° - i \tag{8}$$

The next equation follows similarly:

$$\Phi = 90° - \delta \tag{9}$$

Given these three relationships, spherical geometry can be used to solve the unknowns and ultimately find γ. The next two equations form the basic relations that will allow this to happen:

$$\cos(90° - \phi_{gc}) = \cos(\lambda_{max})\cos(90° - \delta) + \sin(\lambda_{max})\sin(90° - \delta)\cos(90° - \alpha) \tag{10}$$

$$\sin(\phi_{gc}) = \cos(\lambda_{max})\sin(\delta) + \sin(\lambda_{max})\cos(\delta)\sin(\alpha) \tag{11}$$

In these two equations everything is known except δ and α so a relationship is needed between these two angles and something that is known. Again using spherical trigonometry for right spherical triangles the needed relationship can be found:

$$\cos(i) = \cos(\delta)\sin(\alpha) \tag{12}$$

Solving for $\sin(\alpha)$:

$$\sin(\alpha) = \frac{\cos(i)}{\cos(\delta)} \tag{13}$$

Substituting equation (13) into equation (11) and carrying out the cancellation results in the following two equations:

$$\sin(i) = \cos(\lambda_{max})\sin(\delta) + \sin(\lambda_{max})\cos(\delta)\left(\frac{\cos(i)}{\cos(\delta)}\right) \tag{14}$$

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$$\sin(i) = \cos(\lambda_{max})\sin(\delta) + \sin(\lambda_{max})\cos(i) \tag{15}$$

Solving equation (15) for sin(δ) gives:

$$\sin(i) - \sin(\lambda_{max})\cos(i) = \cos(\lambda_{max})\sin(\delta) \tag{16}$$

$$\sin(\delta) = \left(\frac{\sin(i) - \sin(\lambda_{max})\cos(i)}{\cos(\lambda_{max})} \right) \tag{17}$$

Again using spherical trigonometry for right spherical triangles the next relationship is obtained allowing for the calculation of γ, the key to finding answers about coverage:

$$\sin(\Gamma) = \frac{\tan(\delta)}{\tan(i)} \tag{18}$$

$$\gamma = 90° - \Gamma \tag{19}$$

$$\theta_{cov} = 2\gamma \tag{20}$$

From θ_{cov} a relationship showing the amount of time the target is in proper view of the satellite and the orbit plane can be derived and is shown below:

$$T_c = \left(\frac{2\gamma}{360°} \right)(24 \text{ Sidereal Hours}) \tag{21}$$

Now that the angle through with the earth will rotate while the orbit plane is in a position to permit viewing of the target ground station by the satellite has been found, some general equations relating θ_{cov} to coverage time and gap time can be derived. The original derivation of these equations started with the simple case and then progressed to the more complex. First, equations were created for the case of a constellation of one satellite and one plane. From these equations were built the equations for the case of a constellation of multiple (n) satellites and one plane. Finally, the equations for the case of a constellation of n satellites, m planes, and n/m satellites per plane were built. The equations shown below constitute the final set of equations as they represent the case being analyzed here.

Equations for n satellites, m planes, and n/m satellites per plane

1. Number of times a satellite orbits while the target is in view of one orbit plane

$$\frac{T_c}{P} \tag{22}$$

2. Average total time the target is under coverage of all satellites and all planes

$$\left(\frac{\frac{n}{m}mT_c}{P}\right)\left(\frac{T_{FOV}}{2}\right) = \frac{nT_c}{P}\left(\frac{T_{FOV}}{2}\right) \tag{23}$$

3. Time during which the region is not in view of a plane. This represents the time it takes for the target ground station to rotate out from under one orbit plane and into another orbit plane. The equation uses an angle theta non-coverage which represents the angle through which the earth rotates while the target is not in possible view of any satellite in a single plane. This quantity is important because it represents the gap time due to spacing between planes, not the gap time due to the spacing between satellites

$$\theta_{nc}\left(\frac{24 \text{ sidereal hours}}{360°}\right) = T_{nc1} \tag{24}$$

4. Total time during which the target is not in view of any plane. This equation simply multiplies equation (24) by the total number of planes in the constellation

$$m\,\theta_{nc}\left(\frac{24 \text{ siderial hours}}{360°}\right) = T_{nc} = mT_{nc1} \tag{25}$$

5. Time for a single gap in coverage between satellites within one plane

$$\frac{P}{n/m} - \frac{T_{FOV}}{2} \tag{26}$$

6. Total gap time while region is under coverage of one plane

$$\left(\frac{T_c}{P}\right)\left(\frac{n}{m}\right)\left(\frac{P}{n/m}-\frac{T_{FOV}}{2}\right)=\left(\frac{T_c}{P}\right)\left(P-\frac{nT_{FOV}}{2m}\right)=T_c\left(1-\frac{nT_{FOV}}{2mp}\right) \qquad (27)$$

7. Total time region is not under coverage of all planes and satellites. Total gap time

$$T_c\left[1-\frac{nT_{FOV}}{2mp}-m\right]+24 \qquad (28)$$

Before going any further, there is a bit more to discuss with regard to equation (25). This

equation is tells us the time during which there is no plane in the constellation that permits

viewing of the target ground station by a satellite. A simple but interesting result can be gained

from this equation and is discussed below. This discussion assumes a constellation of multiple

(m) orbital planes spaced evenly apart. First, the definition of Theta Non-Coverage is given.

$$\theta_{nc}=\frac{360°-m\theta_{cov}}{m}=\text{Theta Non-Coverage} \qquad (29)$$

$$\theta_{nc}=\frac{360°}{m}-\theta_{cov} \qquad (30)$$

Equation (30) shows that $\theta_{nc} \to 0°$ as $\theta_{cov} \to 360°/m$. Since θ_{cov} depends on the field of view

of the satellite which in turn depends on the altitude of the satellite (in addition to the sensor

type), this relationship can theoretically determine the optimum number of planes for a

constellation of satellites at a particular altitude. So at 300 km, a certain number of planes best

provides full "plane" coverage, and at 800 km, another number of planes best provides full

"plane" coverage. Note once again however that all these results are true only for circular orbits

and for the cases where inclination of the orbit equals latitude of the target.

So finally:

$$\theta_{nc} \to 0° \Rightarrow \frac{360°}{m}-\theta_{cov}=0° \Rightarrow m=\frac{360°}{\theta_{cov}} \qquad (31)$$

Equation (31) gives the number of planes necessary for any constellation to provide coverage such that a satellite can always potentially view the target ground station. This does not mean there is continuous coverage all the time, it simply means there is the potential for continuous coverage. Whether or not it is actually achieved depends on the number of satellites per plane, and the type of sensor on board the satellite.

The results from these equations are shown in Appendix A, Figures A1 through Figures A7. Figure A1 shows the gap time between satellites based on the altitude and the number of satellites per plane. More specifically, it indicates the number of satellites in one plane that is needed in order to provide a particular gap time based on the field of view. For example, in the case where a five minute gap time is desired, 7 satellites per plane are needed. For a twenty minute gap time, about 4 satellites per plane are needed. Note that the altitude has very little effect on this result, at least for altitudes between 300 and 800 km. Also note that only one inclination is shown since inclination of the plane does not affect the gap time between satellites.

Figures A2 through A4 the total time the target is not visible by a satellite in any plane. This is shown at three different inclinations because coverage by plane varies with inclination. What is important here is the fact that for low inclinations around 30°, two planes are enough to provide a situation where the target is always in view of a plane. For the cases where the inclination is greater, like around 37° to 50°, three orbit planes are needed to provide the same coverage. From this it can be concluded that with three planes, full coverage by plane can almost always be guaranteed.

Figures A5 through A7 show the total time the target is not covered by m number of planes and one satellite per plane, or the total non-coverage time. As with Figures A2 through A4, this measure is also shown at three different inclinations because the coverage is affected by

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the inclination. Note that these figures show that non-coverage time can quickly become

negative. This result is misleading because it implies continuous coverage. For example, in

Figure A6 for the case of four planes and one satellite per plane, the graph claims that there is a

negative non-coverage. This implies that four orbiting satellites will provide 100% continuous

coverage of a target at 37° latitude. From common sense, this result most likely is not true. The

reason for this misleading result is the fact that the equations upon which these figures are based

are somewhat basic and simply lump raw times together without taking into account phasing of

satellites and other details that come into play in the reality of complex orbital mechanics. As a

result, the actual numbers themselves may be a bit erroneous and/or misleading, however, the

trends that they show tend to be valid. For example, as the number of planes increases, coverage

gap decreases, which makes sense because as the earth rotates out from under one plane, it is

rotating under another and under the coverage of more satellites. In addition, as the inclination

increases, the gap also increases, which is the same trend shown in Figures A2 through A4 and

occurs for the same reason.

After looking at these results, an interesting question comes to mind. In particular,

looking once again at Figure A2, one plane does not provide full "plane" coverage of the target,

but two planes do. This means that geometrically, one plane handles about 180° of the earth.

This characteristic only seems to take place at lower inclinations. The question then is, what

happens when the inclination is even lower or somewhere very close to λ_{max}, like around 20°? In

this case, for altitudes ranging from 300 km to 800 km and a minimum elevation mask of 10°,

λ_{max} is between 34° and 36°. It turns out that when the latitude of the ground station is about 5°

to 6° less than λ_{max}, the satellite can see the target for 180° of the earth's rotation. This means

that with one plane, the target ground station is in view of the orbit plane for exactly 180°, or half

the time. The other 180° is uncovered by the plane such that the satellite will not be able to see the target. So, in this case, if a second plane is added, each plane will cover 180° for a total coverage of 360° or all of the earth's rotation. This explains why, in Figure A2 at 30° inclination, only two planes are needed to provide full "plane" coverage. Therefore, when the target location lies on a latitude around 28° to 30°, the U.S. can deploy space assets from CONUS and still provide near full plane coverage with two planes.

The flip side of the previous discussion is what happens when the latitude of the target ground station is very high, like around 60° to 90°. Again the result depends upon λ_{max}. The analysis of this particular question shows that at the point where the co-latitude is one fourth of λ_{max}, there is a singularity in the calculations, or basically the equations derived earlier begin to fail. This situation is shown below in Figure 4.

View from North Pole
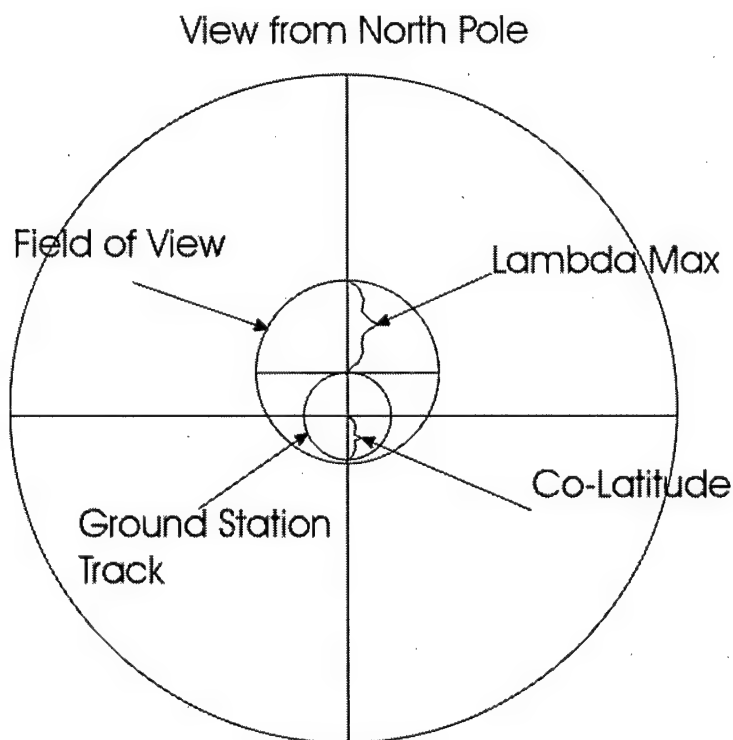
Figure 4. Satellite FOV Geometry Viewed From the North Pole

In this particular case , the footprint of the satellite will always see the target ground station at the top of its orbit. However, there is no distance through which the earth will rotate such that another plane will make up for its non-coverage. What this ultimately means is that for cases of really high inclination, where the co-latitude equals one fourth λ_{max}, it makes little sense to have more than one plane if the mission is to cover a particular region on the earth's surface. In this case, all that needs to be considered is the desired gap time between satellites. Once this is known, in addition to the period P of the satellite and the coverage time T_{FOV} found in equation (6), the number of satellites (n) needed to provide the desired gap time is:

$$n = \frac{P}{T_{gap} + T_{FOV}} \qquad (32)$$

So the options to provide coverage at high latitudes are:

1. One plane with n satellites calculated from equation (32) and a desired predetermined gap time T_{gap}.
2. n planes with one satellite per plane and proper phasing between the satellites to ensure the desired gap time is met.

Option 1 seems the easier of the two, both to build and then to maintain the constellation.

From this analytical analysis, it is possible to begin answering the last two questions about coverage, namely how many planes and how many satellites per plane will be needed? First, Figure A1 in Appendix A shows the necessary number of satellites per plane. If there are three satellites per plane, then there is about 25 minutes of gap time between satellites. If there are five satellites per plane, there is a gap time of about ten minutes between satellites. Furthermore, to get continuous coverage or no gap time between satellites in a single plane, either seven or eight satellites are needed. In addition, it is also known how many planes are needed in the constellation. If the inclination is low, around 20°, then two planes should be enough to have full "plane" coverage. At a higher inclination, around 40°, three planes will

most likely be necessary. Therefore, considering the fact that most of the potential target nations

will be within 50° of the equator, two or three orbit planes will most likely achieve near

complete plane coverage.

STK SIMULATION

The next portion of this study proves the analytical results with a simulation. For this

study, the Satellite Tool Kit (STK) simulation software created by Analytical Graphics was

used. STK is a simulation software that offers many different modules for analyzing all sorts of

satellite system configurations. The module used for this simulation was the coverage module,

along with an attached Figure of Merit. There are about eight Figures of Merit offered. The one

used here is the Revisit Time which is essentially the same thing as gap time. Additionally, the

STK coverage module provides different features as objects for coverage. One such feature is

the Area Target. The Area Target feature is perfect for this simulation as it is possible to model

particular countries as targets, such as Iraq and Libya. With these Area Targets defined, both

the gap time and the number of planes necessary to provide a particular type of coverage could

be analyzed. There are three basic ideas that this simulation will try to prove:

1. An area of non-plane coverage exists for a two plane constellation at an inclination of
   40°. Then show that a third plane eliminates this non-plane coverage.
2. Show that two planes can give complete "plane" coverage below an inclination of
   about 20°.
3. Show that a gap time of 25 minutes exists for a case of three satellites per plane.
   Then show that a gap time of ten minutes exists for a case of five satellites per plane.

In order to show these results, four STK scenarios were created. Each scenario occurs at

an altitude of 500 km simply because the difference between 300 km and 800 km did not affect

the results significantly. The four scenarios are described below in Table 3.

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Scenario	# Planes	Sat/Plane	Inclination (deg)	Altitude (km)	Figures/ Appendix B
1	2	3	40	500	B1, B2
2	2	3	20	500	B3, B4
3	3	3	40	500	B5, B6
4	3	5	40	500	B7, B8

Table 3. STK Scenario Description

The figures listed in the last column of Table 3 show the results of these STK simulation scenarios. The odd rows show gap duration. The even rows show current and accumulated coverage.

Figures B2 and B6 from scenarios 1 and 3 answer the first question about non-plane coverage. Figure B2 shows two rather large gaps and then several small gaps. The small gaps indicate the gap time between satellites. The large gaps indicate gaps between planes. It is during these large gaps when no plane can provide coverage of the target ground station. Figure B6, on the other hand, shows none of the large gaps, just small gaps. Furthermore, the only difference between the two figures is that Figure B6 includes three planes and Figure B2 includes two planes. This result proves that at high inclinations, three planes are necessary to provide zero non-plane coverage.

Figure B4 of scenario 2 answers the second question about the number of planes needed at low inclinations. Scenario 2 is exactly the same as scenario 1 but the inclination is lower, in this case 20°. Figure B4 again shows the current and accumulated coverage. Note that the two large gaps, similar to Figure B2, begin to appear. However, they are not complete gaps. This figure shows that 20° is the threshold between needing two or three planes. If the orbit inclination is lower than 20°, two planes are sufficient-any higher and three planes are needed to provide zero non-plane coverage.

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Figures B5 and B7 from scenarios 3 and 4 provide answers to the third question about gap times. Figure B5 shows that approximately 94% of the target area has a gap time under 27 minutes. Figure B7 shows that approximately 94% of the target area has a gap duration under 14 minutes. These results are approaching the expected results for gap times. Going a bit further and using the Figure of Merit for Revisit Time to get an actual number for the gap times, the revisit time for scenario 3 came to under 27 minutes. The revisit time for scenario 4 came to under 14 minutes. These gap times are about 3 minutes greater than those predicted with analytical results in Figure A1 discussed earlier. This discrepancy can most likely be attributed to errors surrounding the derivation of equation (26). Equation (26) uses an "average" time in view to calculate the gap time, whereas STK uses numerical calculation and is probably a little more accurate than the analytical formulas provided here. Nonetheless, the results from both STK and the analytical results point in the same direction and provide the same conclusions regarding coverage. These results are summarized in the statements given below:

- For inclinations lower than 20°, two planes are sufficient to provide zero non- plane coverage.
- For inclinations greater than or equal to 20° and less than 50°, three planes are sufficient to provide near complete plane coverage.
- For gap times of about ten minutes, five satellites per plane are needed.
- For gap times of about 15 to 20 minutes, four satellites per plane are needed.
- For gap times of about 25 minutes, about three satellites per plane are needed.
- For near continuous coverage within a singe plane, greater than eight satellites are needed.

For the purposes of this study, the most general constellation will be a constellation of three planes spaced equally apart with an inclination equal to the latitude of the target country. Furthermore, within the three planes there will be three satellites spaced equally apart. This configuration seems well suited for the combination of MSP/SMV/TACSAT. The MSP can carry three SMVs for pop-up mission and each SMV can carry three TACSATs. If each SMV is

able to get into a separate plane, it will be possible to form the nominal three plane, three satellites per plane constellation. The remaining portion of this study will look at how much ΔV and how much time will be needed to actually create these constellations and whether or not they can be done.

LAUNCH ANALYSIS

The sequence for launching the MSP/SMV/TACSAT combination is simple. With a loaded configuration, the combination will include one MSP with three SMVs. Each SMV in turn will be loaded with three 400 lbs TACSATs. The MSP is a maximum reusable spacecraft capable of single stage to orbit space lift. This study will make four basic assumptions regarding the combination launch sequence.

1. The total time starting from ignition to burnout for the MSP will be a maximum of 500 seconds. This assumes a vertical launch, not a horizontal takeoff.
2. The MSP can carry one SMV fully loaded into direct orbit.
3. The MSP can carry three SMVs for pop-up. At pop-up the MSP will be traveling between 21 and 23 Mach.
4. The SMV will expend approximately 3000 fps ΔV to achieve orbit.

Assumption number one above can be verified with the following equation.

$$h_{bo} = -\frac{1}{2} g t_{bo}^{2} + c t_{bo} - \frac{c t_{bo}}{R-1} LN(R) \tag{33}$$

$$R = \frac{m_o}{m_f} \tag{34}$$

For this equation, $g = 9.81$ m/s^2. $C = (ISP*g)$ where ISP is equal to 440 sec for the MSP.

C is then equal to 4316.4 m/s. Next, $m_o = 1.3$ Mlbs and $m_f = 140$ Klbs. R is then equal to 9.2857.

Plugging these values into equation (33) and solving numerically, the values for t_{bo} are provided in Table 4.

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Altitude at Burn Out (km)	T_{bo} (sec)
300	115.98
400	173.62
500	282.57
600	321.66
700	321.66
800	321.66

Table 4. Burn Out Time for various altitudes

Note that equation (33) assumes that there are no losses except for losses due to gravity. Given this assumption it seems safe to assume a maximum launch time of 500 seconds for the MSP to launch, for the SMV pop-up to occur, and for the SMV to reach its mission orbit.

Assumption four listed above can also be verified with some basic calculations. First the velocity needed to get into orbit must be calculated. The equations that will be used are shown below. These equations take into account the earth's rotation and are expressed in the SEZ coordinate system.

$$\mathbf{V_N} = \begin{bmatrix} -V_{bo} \cos\phi_{bo} \cos\beta_{bo} \\ V_{bo} \cos\phi_{bo} \sin\beta_{bo} - 0.4651\cos\phi_{bo} \\ V_{bo} \sin\phi_{bo} \end{bmatrix} \tag{35}$$

This equation gives $\mathbf{V_N}$ expressed in km/s. V_{bo} is the velocity at burn out or the orbit velocity. ϕ_{bo} is the flight path angle which is zero degrees because the orbits are circular. β_{bo} is the burn out azimuth and, in this case, is equal to the co-latitude or the co-inclination. Given assumption three above, the next task is to calculate the velocity of the MSP at Mach 21 and 23 for pop-up missions. Without going into the details, the velocity of the MSP at Mach 21 is 6.6549 km/s and at Mach 23 is 7.2887 km/s. With these two pieces of information the ΔV that the SMV must provide in order to achieve orbit after pop-up can be calculated and is given in Table 5 below.

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Altitude (km)	Velocity Initial (km/s)	Magnitude V_N (km/s)	Mach 21 ΔV for SMV (fps)	Mach 23 ΔV for SMV (fps)
300	7.726	7.379	2377	298
400	7.668	7.322	2190	110
500	7.612	7.266	2006	-72
600	7.557	7.211	1827	-252
700	7.504	7.158	1651	-427
800	7.451	7.105	1479	-599

Table 5. SMV ΔV for Pop-Up Mission Scenarios

The fourth and fifth columns show the ΔV needed by the SMV to obtain orbit after pop-up at Mach 21 and Mach 23 respectively. This shows a worse case ΔV needed by the SMV of 2377 fps. For the remaining portion of this study, a worst case ΔV of 3000 fps is assumed, which is the same assumption made earlier.

PLANE CHANGE ANALYSIS

Within the analysis of the ΔV budget, the ΔV requirement for plane change is the most expensive. Given that the plane change does not change the inclination of the orbit the following equations were used [7].

$$\cos(\alpha) = \cos^2(i) + \sin^2(i)\cos(\Delta\Omega) \tag{36}$$

$$\Delta V = 2V_{initial} \sin\left(\frac{\alpha}{2}\right) \tag{37}$$

With these equations, Figures C1 and C2 in Appendix C were created. Figure C1 shows the ΔV that is needed for inclinations from 0° to 50°. This figure assumes a three plane constellation equally spaced apart by 120°. 120° is used because the coverage analysis showed that three planes would normally be sufficient to provide full "plane" coverage. Figure C1 reveals that inclination does have a significant affect on ΔV. Figure C2 is basically the reverse

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of Figure C1 and shows the ΔV needed for different longitudes of the ascending node. Here the inclination is held constant at 30°. Note that the ΔV needed for a 120° $\Delta\Omega$ change is 21951 fps. The SMV nominally has 9000 fps ΔV after pop-up. Even with auxiliary fuel tanks, the SMV cannot do a 120° plane change, phase all the satellites, and de-orbit. Given this, a 120° orbit plane change is out of the question. In order to get the coverage that is desired, another MSP will need to be launched. Knowing that inclination also affects the ΔV needed for plane changes, Figures C3 and C4 were created. C3 shows the ΔV needed for various plane change angles for a constellation at 50° inclination. This is even worse than that shown in Figure C2. For 50° inclination, the SMV with auxiliary fuel tanks can only perform plane changes up to a maximum of 40°. Again, in order to get the coverage that is desired, more than one MSP must be launched.

Figure C4 paints a more positive picture. With auxiliary fuel tanks, the SMV can potentially perform a 110° plane change. This is getting closer to being able to create an equally spaced three plane constellation. However, the coverage analysis showed that a two plane constellation would be enough if the inclination were lower than about 20°. So the problem is that, despite the fact that a three plane constellation can almost be formed, it is not really needed if complete plane coverage is characteristic to be achieved.

PHASING ANALYSIS

Before any recommendation can actually be made on what launch configuration would be most suitable for these different situations, a phasing analysis must be made. Phasing involves the process of spreading out satellites in an orbit so they are equally spaced. For example, if there is one SMV per plane, then it is possible to have three satellites per plane spaced 120°

apart. There are two basic scenarios that can take place and are depicted in Figures 5 and 6
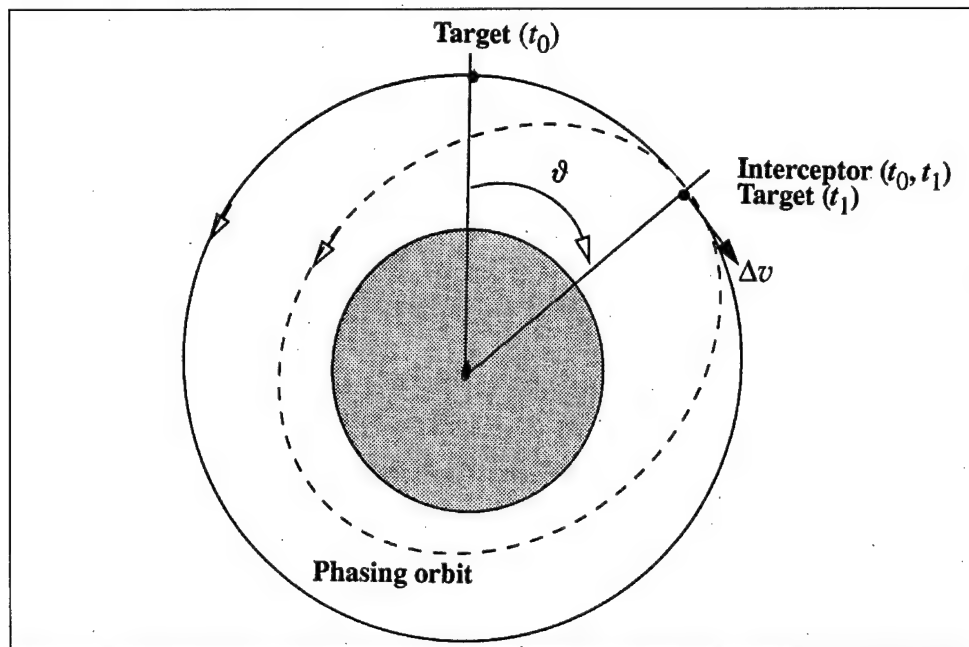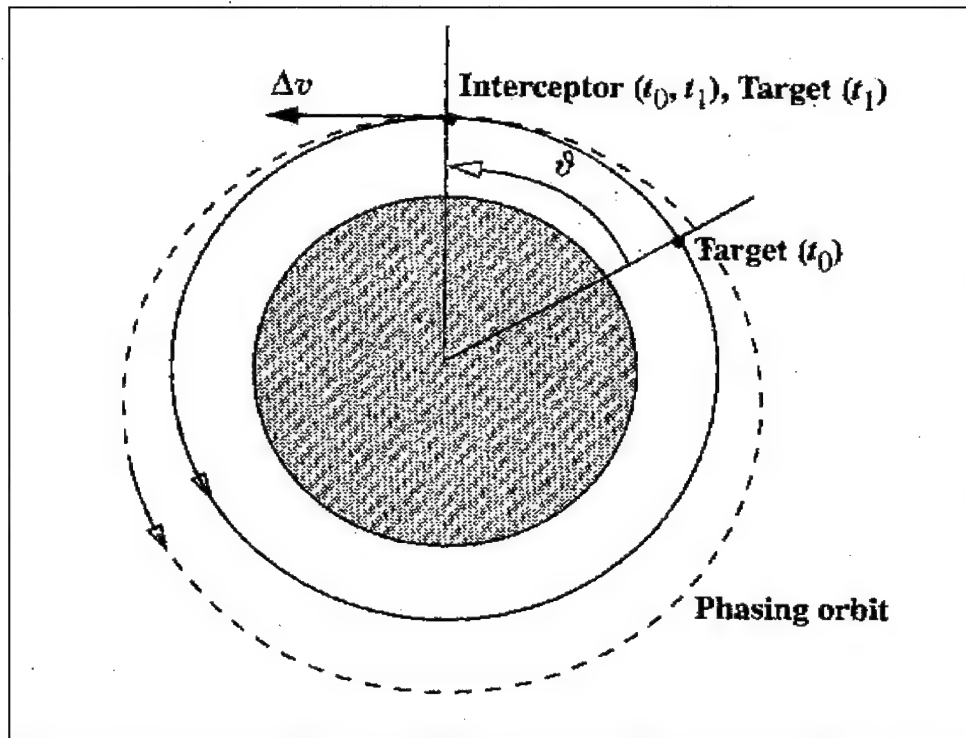
below.

Figure 5. Geometry of Phasing Maneuver for Target Leading Interceptor [8]

Figure 6. Geometry of Phasing Maneuver for Interceptor Leading Target [8]

For the case shown in Figure 5, the interceptor will need to enter into an orbit with a period less than its original orbit. This is because the interceptor must travel around some orbit and return to the same spot in the same amount of time that the target travels $360° - v$, which is less than one orbit. The exact opposite case holds in Figure 6. In either case, some ΔV must be spent and some time is going to pass. The question is, how much ΔV and how long is it going to take? Before addressing this question, it is necessary to discuss two parameters that are used in the calculation of phase time and ΔV. The two parameters are K_{int} and K_{tgt}. K_{int} simply means the number of times the interceptor travels around the phasing orbit, and K_{tgt} is the number of times the target travels around the original orbit. Note that the interceptor is the SMV, and the target is where the SMV wants to deploy another satellite.

After experimenting with the values of K_{int} and K_{tgt}, it was found that the scenario of "interceptor ahead of target", as depicted in Figure 6, was the only viable option. This has to do

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with the fact that in Figure 5, the perigee radius of the phasing orbit was too short, in which case

the SMV would simply burn into the atmosphere. Therefore, the only case being considered

here is the case where the interceptor is ahead of the target. For this scenario it was found that the

best results came about when $K_{int} = K_{tgt}$. This information is shown in Tables 6, 7, 8, and 9

below.

$K_{int} = K_{tgt}$	300 Km	400 Km	500 Km	600 Km	700 Km	800 Km
1	2420	2400	2380	2370	2350	2330
2	1300	1290	1280	1270	1260	1250
3	890	883	877	870	864	858
4	676	671	666	661	657	652

Table 6. ΔV (fps) needed to phase 6 satellites per plane

$K_{int} = K_{tgt}$	300 Km	400 Km	500 Km	600 Km	700 Km	800 Km
1	1.76	1.78	1.84	1.88	1.92	1.96
2	3.27	3.34	3.42	3.49	3.57	3.64
3	4.78	4.89	4.99	5.10	5.21	5.32
4	6.29	6.43	6.57	6.71	6.86	7.00

Table 7. Time (hours) needed to perform a single phasing maneuver of 60°

$K_{int} = K_{tgt}$	300 Km	400 Km	500 Km	600 Km	700 Km	800 Km
1	4250	4210	4180	4150	4120	4100
2	2420	2400	2380	2370	2350	2330
3	1690	1680	1670	1650	1640	1630
4.	1300	1290	1280	1270	1260	1250

Table 8. ΔV (fps) needed to phase 3 satellites per plane

$K_{int} = K_{tgt}$	300 Km	400 Km	500 Km	600 Km	700 Km	800 Km
1	2.01	2.06	2.10	2.15	2.19	2.24
2	3.52	3.60	3.68	3.76	3.84	3.92
3	5.02	5.14	5.26	5.37	5.49	5.60
4	6.54	6.68	6.83	6.98	7.13	7.28

Table 9. Time (hours) needed to perform a single phasing maneuver of 120°

From these tables, it can be seen that as $K_{int} = K_{tgt}$ increases, ΔV drops but only at the expense of

time. Based on the analysis of the plane change, the case when $K_{int} = K_{tgt} = 1$ most likely will not

be feasible because the ΔV will be too large. Whether or not the other options are feasible

depends on how the constellation is set up. Combining data from the phasing and plane change analyses, the recommended options are given below in Tables 10 and 11.

Scenario	Inc (deg)	MSP	#SMV/ MSP	$\Delta\Omega$ (deg)	ΔV (fps)	$K_{int} = K_{tgt}$	ΔV (fps)	Phase Time (hrs)	ΔV total (fps)
1	50	2	3	35	11678	3	3380	10.06	18058
2	50	3	1	0	0	1	8500	4.02	8500
3	30	2	3	60	12674	3	3380	10.06	19054
4	30	3	1	0	0	1	8500	4.02	8500
5	20	2	3	60	8669	2	4840	7.04	16509
6	20	2	1	0	0	1	8500	4.02	8500

Table 10. Constellation Deployment Scenarios – Three Satellites Per Plane

	Inc (deg)	MSP	#SMV/ MSP	$\Delta\Omega$ (deg)	ΔV (fps)	SMV1 ΔV (fps)	Phase Time (hrs)	$K_{int} = K_{tgt}$	SMV2 ΔV (fps)	Phase Time (hrs)
7	50	3	2	0	0	4840	3.52	2	8280	8.80
8	30	3	2	0	0	4840	3.52	2	8280	8.80
9	20	2	2	0	0	4840	3.52	2	8280	8.80

Table 11. Constellation Deployment Scenario – Six Satellites Per Plane

In all but one case in Tables 10 and 11, the planes are equally spaced apart. The first row of Table 10 indicates a case where the planes will not be spaced apart equally which will have an effect on the gap time and will also result in a period of non- plane coverage. Figure B9 and B10 show the results of this particular constellation.

Table 10 shows cases for having three satellites per plane. Table 11 shows cases for having six satellites per plane. These tables differ in their phasing sequence. In Table 10, one SMV must phase twice for 120°. In Table 11, one SMV will phase twice for 60°, the second SMV must first phase 180°, then phase twice for 60°. In order to show the results, Table 11 is broken down to show the ΔVs and phase times for both SMVs because they will not be the same.

In these tables, the inclinations were chosen because they represent a certain situation. The 50° inclination generally represents a limit. For example, if the target ground station lies between 50° and 30°, the 50° case can be performed in order to build the constellation and still have a ΔV margin left over. The 30° inclination represents an average case. In this situation, a 60° plane change can barely be performed, but it is still possible. With two MSPs, this gives six orbit planes spread equally apart. With six planes and three satellites per plane, the target ground station will have constant plane coverage and a maximum 25 minute gap time. However, this gap time will likely be less because there is so much overlap between the six planes. Finally, the 20° inclination case is shown because it represents the case where only two planes are needed to get complete plane coverage. For this reason, only two MSPs are ever needed.

TIMING

The last topic that will be covered is timing. As stated earlier, the one primary characteristic of the MSP is responsiveness and its ability to perform missions quickly and efficiently upon notice. [5]. Based on given requirements, how fast can the MSP/SMV/TACSAT combination deploy and how does this responsiveness compare to similar military systems? More to the point, does this combination out perform current systems in both time and coverage? Before presenting the results of this analysis, there are a few considerations that should be discussed. These are listed below:

1. How quickly can the MSP and the SMV be prepared for a full flight mission upon notice?
2. How many MSPs are in inventory and/or are mission capable?
3. Does the rotation of the earth affect launch time?
4. How long does a plane change maneuver take?
5. How long does a phasing maneuver take?

To answer the first question, there are system requirements that specify the turn around times for the MSP and SMV. The Technical Requirements Document for the SMV states that:

1. The SMV can be prepared for launch in 12 hours [4].
2. SMV can be loaded onto the MSP in about 4 hours [4].

For the purposes of this study, it will be assumed that the SMV will be prepared and loaded either before hand or in parallel with the preparation of the MSP. Given this, the SMV preparation time will not affect the actual mission times calculated here.

For the MSP, the Spaceplane System Capstone Requirements Document provides the following turn around times.

1. During peacetime, the MSP can be prepared for mission execution within 2 days.
2. During wartime, the MSP can be prepared for mission execution within 12 hours.

To answer the second question, two cases will be considered. The first case will assume only one MSP exists and is capable of mission execution. The second case will assume a minimum of three MSPs exist and are capable of mission execution. The reason for these two choices is largely arbitrary and simply are intended to show a comparison.

To answer the third question, the earth's rotation does have a large affect on launch windows. Closely tied to this question is the assumption that all the MSPs will be launched from the same location, which is the assumption made here. For example, a two plane constellation will require two launches, the second launch of which will have to come twelve hours or 180° of earth rotation after the first. For a three plane constellation, three launches will have to take place, the second and third of which take place eight hours or 120° of earth rotation after the previous launches. The number of MSPs that are mission capable also plays into this calculation. If only one MSP is mission ready, then mission timing will depend both on the MSP turn around

time as well as the launch window. If more than one MSP is mission ready, then mission timing will depend only on the launch window.

To answer question number four, it is assumed that the plane change maneuver is performed by a ΔV which is impulsive and instantaneous. Essentially then, the plane change will take no time. However, for the plane change to work, the SMV must be at the correct location in the orbit before the burn can take place. On average, each SMV will be one half orbit away from the correct plane change location upon orbit insertion. Given that the orbit times are approximately 95 minutes at an altitude between 300 km and 800 km, this means that on average the SMV will need to perform a plane change within about 47 minutes of orbit insertion. However, in order to take into account any unusual circumstances and other complications, a 95 minute plane change time will be assumed for worst case.

Finally, to answer question number five, phasing time is already calculated and shown in Tables 10 and 11. Shown below, in Tables 12, 13, and 14, are the timing calculations for the specific scenarios given in Tables 10 and 11. Times are shown for cases of peacetime and wartime, with either one or three mission capable MSPs. Note that in these tables, the preparation time shown in the second column includes the MSP and SMV preparation times as well as the wait time for earth rotation and launch window set up. Also, since launch and orbit insertion time will take about 500 seconds for all cases, it is not shown in the tables below.

Scenario	Prep Time (days)	Plane Change Time (min)	Phase Time (hrs)	Total Time (hrs)
1	2	95	10.06	59.76
2	4	0	4.02	100.08
3	2	95	10.06	59.76
4	4	0	4.02	100.08
5	2	95	7.04	56.88
6	2	0	4.02	52.08
7	4	0	8.80	104.94
8	4	0	8.80	104.94
9	2	0	8.80	56.94

Table 12. Total Mission Times during peacetime with one MSP capable

Scenario	Prep Time (hrs)	Plane Change Time (min)	Phase Time (hrs)	Total Time (hrs)
1	12	95	10.06	23.78
2	32	0	4.02	36.16
3	12	95	10.06	23.78
4	32	0	4.02	36.16
5	12	95	7.04	20.76
6	12	0	4.02	16.15
7	32	0	8.80	40.94
8	32	0	8.80	40.94
9	12	0	8.80	20.94

Table 13. Total Mission Times during wartime with one MSP capable

Scenario	Prep Time (hrs)	Plane Change Time (min)	Phase Time (hrs)	Total Time (hrs)
1	12	95	10.06	23.78
2	16	0	4.02	20.16
3	12	95	10.06	23.78
4	16	0	4.02	20.16
5	12	95	7.04	20.76
6	12	0	4.02	16.15
7	16	0	8.80	24.94
8	16	0	8.80	24.94
9	12	0	8.80	20.94

Table 14. Total Mission Times during peacetime/wartime with three MSPs capable

Notice that Table 14 shows both the war and peacetime cases with three MSPs being

mission capable as having exactly the same total mission times. This is due to the fact that the

mission can be planned such that while one MSP is flying, the other is being prepared or has already been prepared for flight. Therefore, when the earth has rotated into the proper position, the next MSP is ready for launch. For these two cases the turn around and preparation times for the MSP do not come into play. Only the earth's rotation and launch window set up matters.

The analysis reveals that the worse case mission execution time is about 100 hours or a little over four days. This is primarily due to the fact that it can take up to two days to prepare the MSP for flight during peacetime. Even so, the ability to launch and set up an entire constellation of satellites within four days upon notice is outstanding compared to current mission execution times. In direct contrast, the best mission execution time is about 16 hours due to the short turnaround time of the MSP during wartime. The fact that this turnaround time roughly corresponds to about 180° earth orbit time is rather nice and computationally convenient.

CONCLUSION

Overview

In the large scheme of things, satellite coverage analysis is quite complicated. This analysis is one narrow path within a network of possible constellation solutions and it should be recognized as such. The bottom line is that each situation that arises will be handled on a case by case basis. This analysis is aimed towards the military and therefore it builds upon a previous military study suggesting constellations with inclinations equal to the target latitude. It is within this one option that the analysis proceeds. As a result, the latitude of the target nation drives the conclusions that result from the coverage analysis because it alone dictates the inclination of the orbit. Since inclination affects coverage characteristics, the number of planes can change for

each individual situation, which in turn changes the number of MSPs and the number of launches needed. These details in turn affect the time needed for constellation deployment.

Before presenting a summary of the results found within this study, a certain cause and effect characteristic will be assumed. First the criticality of the situation will dictate the response time required. The response time will in turn dictate the type of coverage that can be achieved. Coverage type will dictate the number of orbit planes and the number of satellites per plane, which then dictates the number of MSPs and SMVs required. This is the sequence in which the summary of results will be performed within the following paragraphs. The figure below shows this decision making process in more detail.
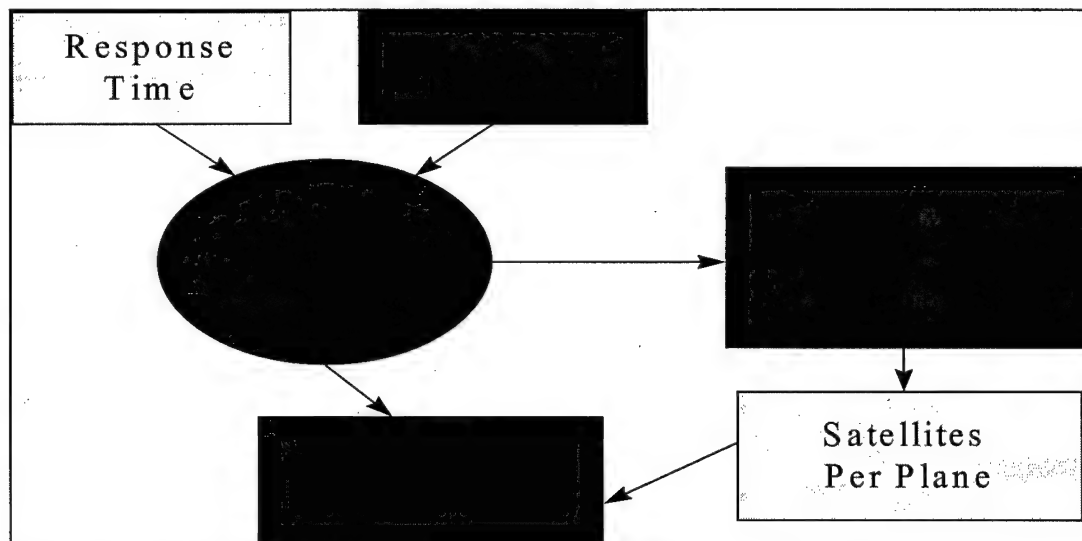
Figure 7. MSP Decision Process

Response Time vs Type of Coverage

The first issue to be discussed will be response time, and the limitations that apply to it are included in the following list:

- Number of MSPs in inventory and are mission capable
- MSP turn around time
- Rotation of the earth affecting launch window set up and longitude of the ascending node of the orbit plane

1 MSP

Wartime

For the case of a wartime scenario with only one MSP in inventory, the following best case response time vs coverage characteristics were found within this analysis:

Response Time (hours)	Latitude of Target Location	Scenario	Satellite Gap Time (minutes)	Plane Gap Time (minutes)
< 16	0° - 20°	---	N/A	N/A
17 – 20	"	6	25	0
> 21	"	9	10	0
< 23	20° - 50°	---	N/A	N/A
24 – 40	"	1 or 3	25	0
> 40	"	7 or 8	10	0

Table 15. Response Time Dictating Coverage Characteristics

Peacetime

For the case of a peacetime scenario with only one MSP in inventory, the following best case response time vs coverage characteristics were found within this analysis:

Response Time (hours)	Latitude of Target Location	Scenario	Satellite Gap Time (minutes)	Plane Gap Time (minutes)
< 52	0° - 20°	---	N/A	N/A
53 – 56	"	6	25	0
> 56	"	9	10	0
< 59	20° - 50°	---	N/A	N/A
60 – 104	"	1 or 3	25	0
> 104	"	7 or 8	10	0

Table 16. Response Time Dictating Coverage Characteristics

3 MSPs

For the case where three MSPs are available to carry out the mission, specification of peacetime or wartime no longer applied. Therefore, the following best case response time vs coverage characteristics were found within this analysis with three MSPs in inventory:

Response Time (hours)	Latitude of Target Location	Scenario	Satellite Gap Time (minutes)	Plane Gap Time (minutes)
< 16	0° - 20°	---	N/A	N/A
17 – 20	"	6	25	0
> 21	"	9	10	0
< 20	20° - 50°	---	N/A	N/A
21 – 23	"	2 or 4	25	0
> 24	"	1 or 3	25	0
> 25	"	7 or 8	10	0

Table 17. Response Time Dictating Coverage Characteristics

Satellites Per Plane

For the purposes of this study, coverage had two primary limitations after certain assumptions were made such as altitude, eccentricity, and inclination. These two primary limitations were

- The number of orbital planes within the constellation
- The number of satellites per plane

It turns out that inclination as well as the number of planes affects the plane gap time, which is why for different inclinations, a different number of planes are specified to provide full plane coverage.

- If the latitude of the target location is between 0° - 20°, the number of orbital planes needed for complete plane coverage is two
- If the latitude of the target location is between 20° - 50°, the number of orbital planes needed for complete plane coverage is three.

The number of satellites per plane affects the gap time between satellites and is not affected by the inclination. The following table summarized the relationship between satellite gap times and

number of satellites per plane, which is the same regardless of the latitude of the target location or the number of planes in the constellation.

Satellite Gap Time (minutes)	Number of Satellites per Plane
0	9
5	7
10	5
15	4
20	4
25	3

Table 18. Satellite Gap Time vs Number of Satellites Per Plane

Resources Required

Finally, the coverage desired (the number of planes and satellites per plane) in turn affects the number of MSPs and SMVs required to accomplish the mission. The following two tables summarize this relationship and take into account the fact that the SMV does not have the capability to perform large longitude of the ascending node plane changes.

Number Satellites Per Plane	Number of Planes	Number of MSPs	Number of SMVs/MSP
9	2	2	3
7	2	2	3
5	2	2	2
4	2	2	2
3	2	2	1

Table 19. Required Resources

Number Satellites Per Plane	Number of Planes	Number of MSPs	Number of SMVs/MSP
9	3	3	3
7	3	3	3
5	3	3	2
4	3	3	2
3	3	3	1

Table 20. Required Resources

It can be seen from these tables that the number of MSPs required depends on and is equal to the number of planes required in the constellation. Again, this is due to the fact that the SMV simply

cannot perform large plane changes. As a result, the MSP winds up building the planes, and the SMV performs the satellite phasing within the plane. However, the reader should be reminded that the SMV can perform smaller longitude of the ascending node plane changes meaning that different constellations can be built besides the nominal three and two plane constellations shown here. Examples of these are shown in the text in Table 6, scenarios 1, 3, and 5.

One example of how this MSP satellite constellation deployment system may compare to other United States Air Force surveillance and reconnaissance systems is provided in Appendix E. The system being compared is JSTARS.

Finally, despite the fact that this study is one narrow option among many, and within the validity of the MSP turn around times, the analysis does paint a picture of the feasibility of the MSP in future military surveillance and reconnaissance missions. It is my feeling that if the MSP and all of its required technologies are realized, and if the cost of space launch is significantly reduced, the MSP does represent a viable option for fulfilling the Air Force mission elements of Space Support and Force Enhancement. In terms of how this project could be enhanced with future research, I would suggest relaxing three of the constraints, namely (1) vary the number of target locations, (2) do not limit the inclination of the orbit planes to the latitude of a target location, (3) vary the number and location of MSP system launch sites. I would imagine that performing an analytical analysis for this type of research would become quite complicated and tedious. In fact, given all the software analysis tools available today, an analytical analysis would probably be a waste of time and possibly even less accurate. However, by varying these variables, I think the results found would be more general and perhaps more applicable to real world situation than those found within this particular study.

APPENDIX A
FIGURES FOR ANALYTICAL COVERAGE ANALYSIS

Figure A1

# Planes Vs Non Plane Coverage
i = 30 degrees

Legend:
- 300 Km
- 400 Km
- 500 Km
- 600 Km
- 700 Km
- 800 Km

Time Non Plane Cov (Sid Hrs)

Orbit Planes

Altitude (Km)

800 Km
700 Km
600 Km
500 Km
400 Km
300 Km

Figure A2

51

# Planes Vs Non Plane Coverage
i = 37 degrees

Legend:
- 300 Km
- 400 Km
- 500 Km
- 600 Km
- 700 Km
- 800 Km

Time Non Plane Cov (Sid Hrs)

Orbit Planes

Altitude (Km)
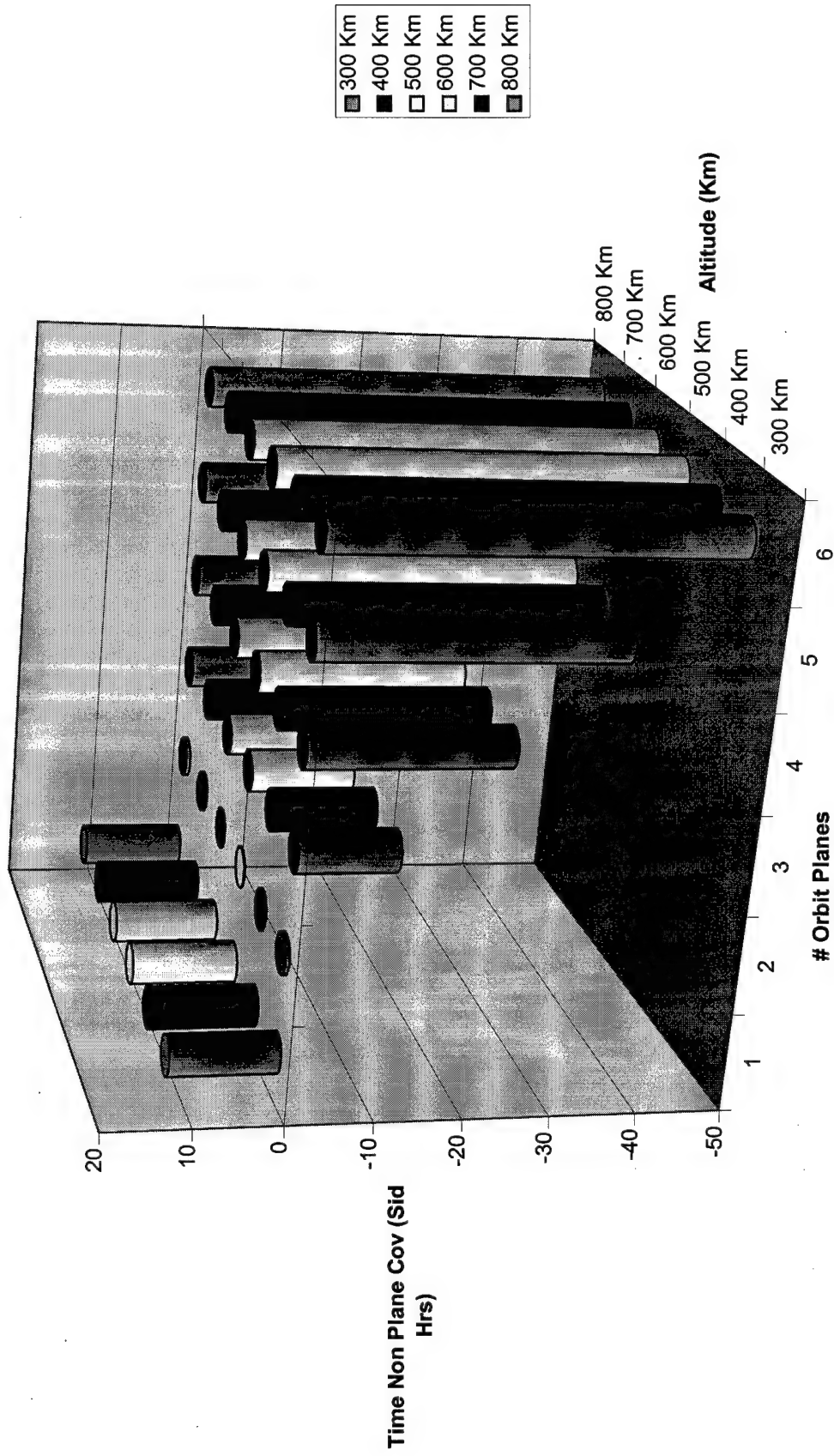
Figure A3

52
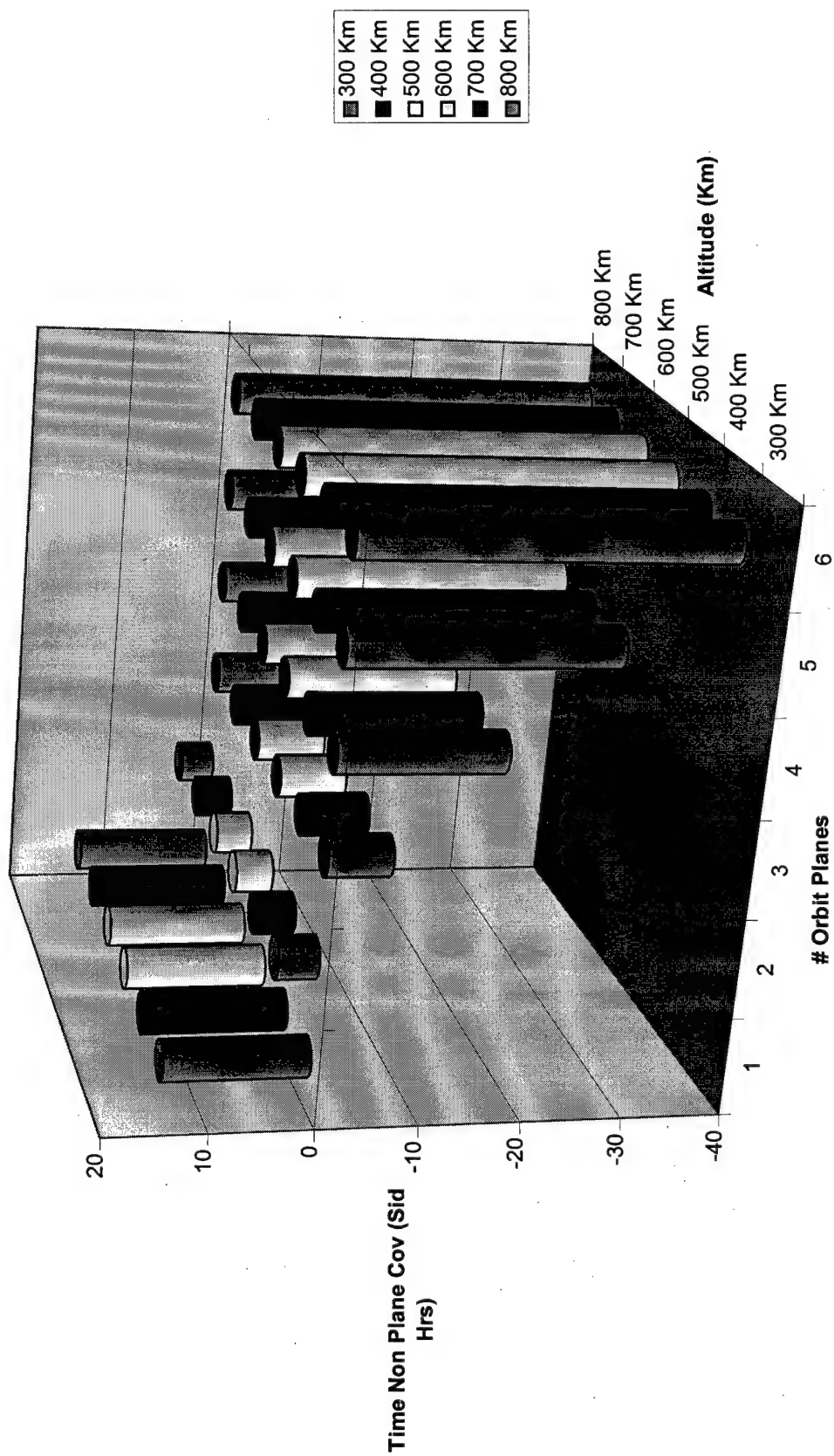
# Planes Vs Non Plane Coverage
i = 45 degrees

Altitude (Km)

800 Km
700 Km
600 Km
500 Km
400 Km
300 Km

300 Km
400 Km
500 Km
600 Km
700 Km
800 Km

Time Non Plane Cov (Sid Hrs)

Orbit Planes

Figure A4

53
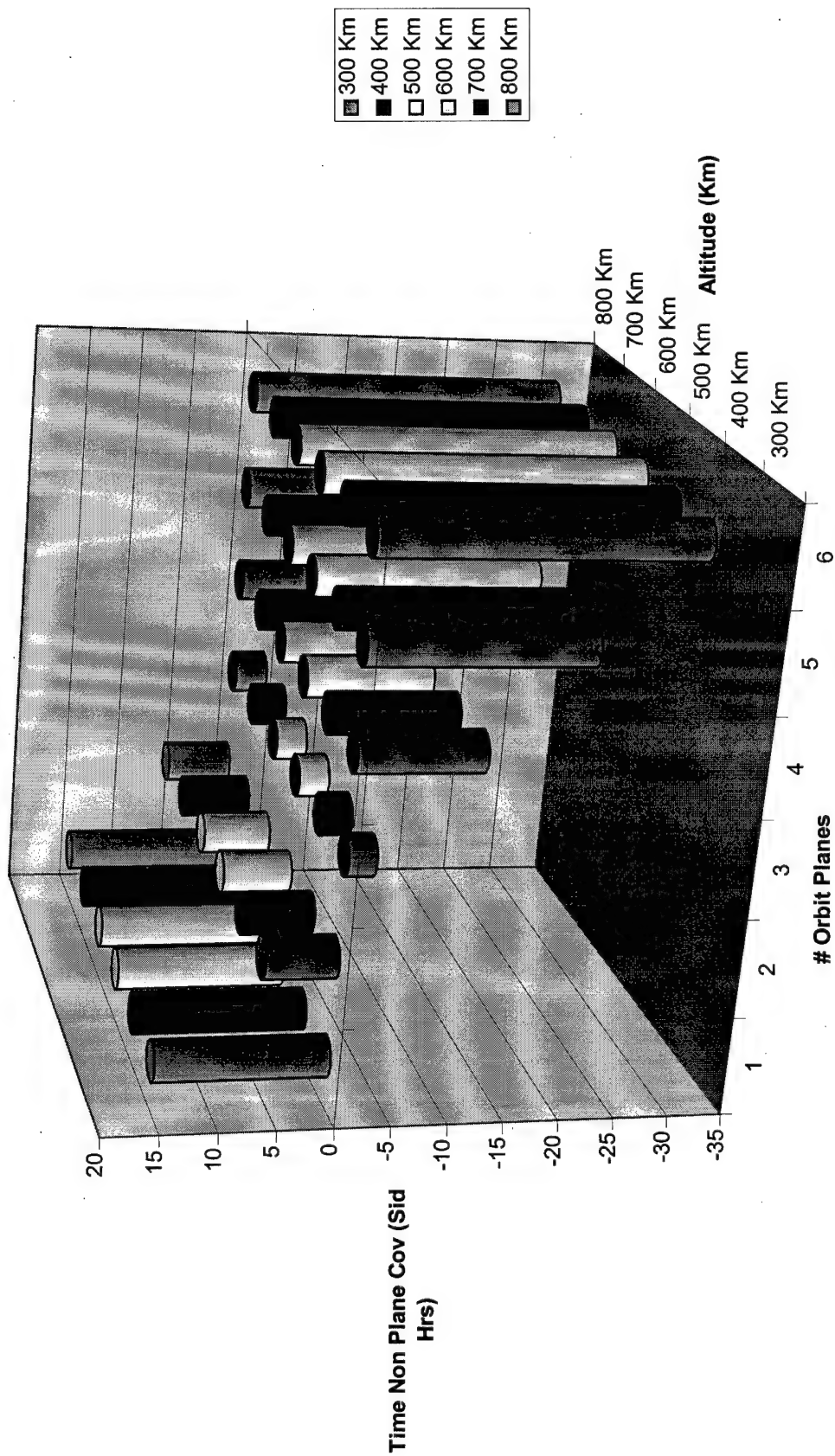
Figure A5

Total Non-Coverage Time Vs # Satellites & # Planes
i = 30 degrees

Total Non-Coverage Time Vs # Satellites & # Planes
i = 37 degrees
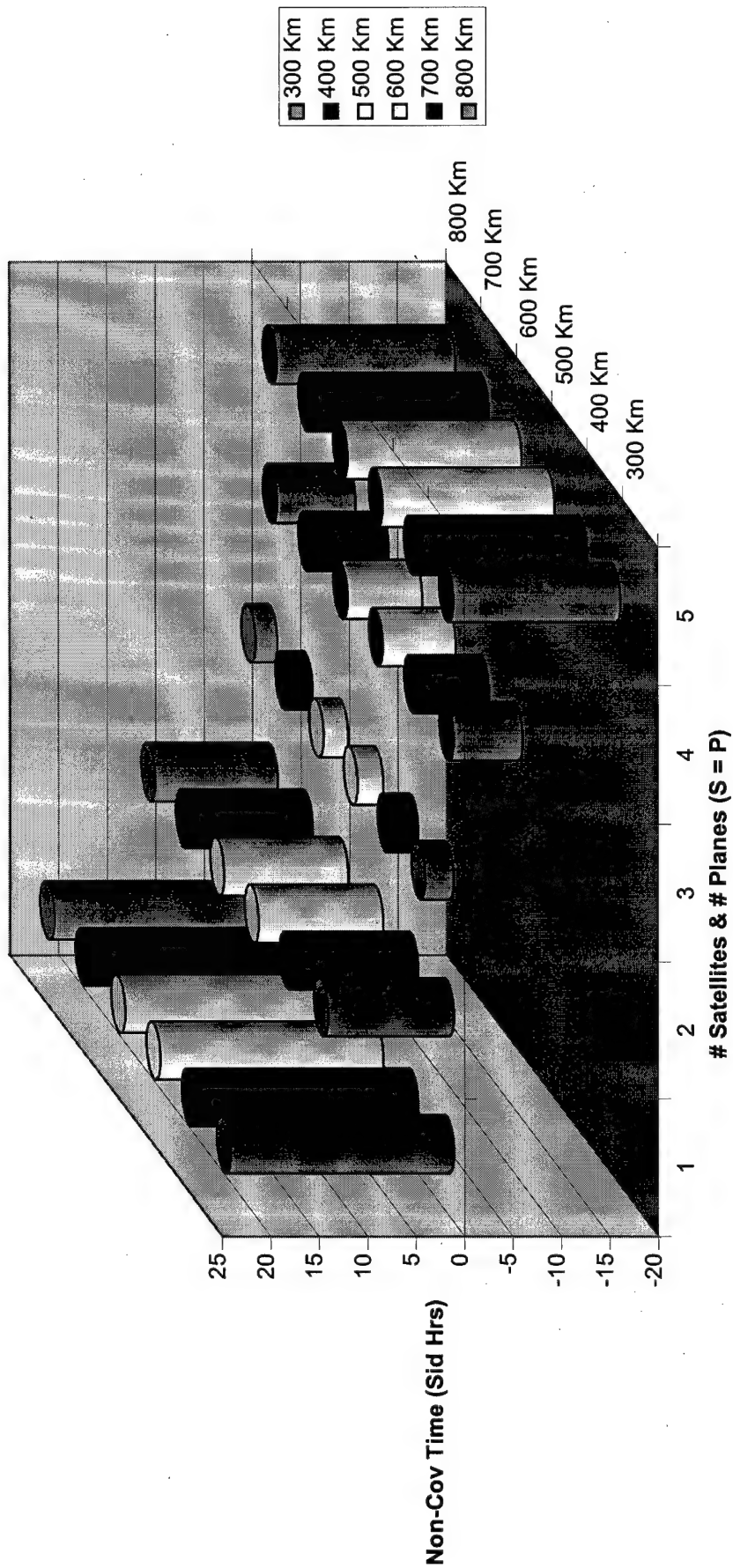
Figure A6

Figure A7

56
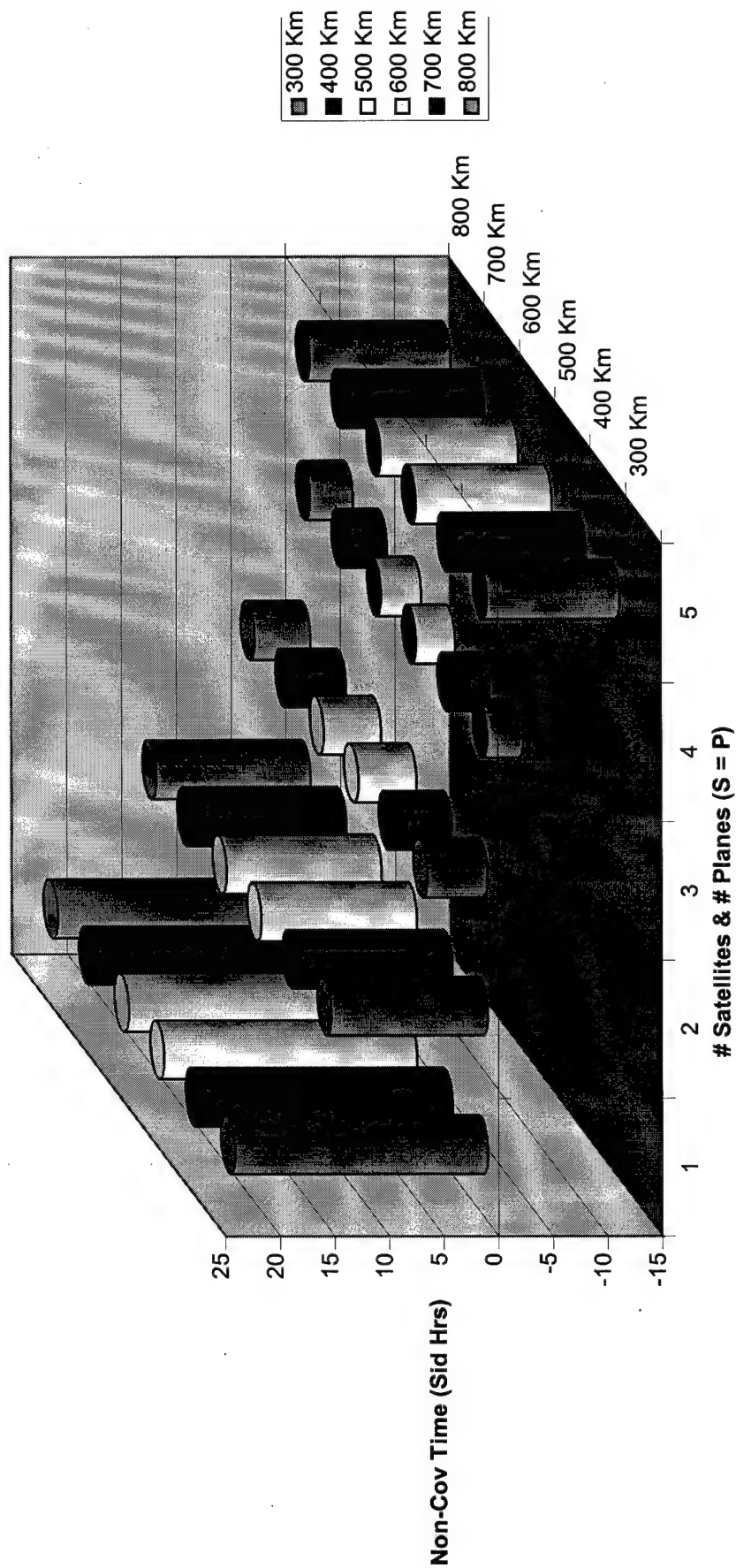
APPENDIX B
FIGURES FOR STK SIMULATION COVERAGE ANALYSIS

Gap Time

% Accesses

100
80
60
40
20
0

0.106   138.045   275.985

Duration (min)
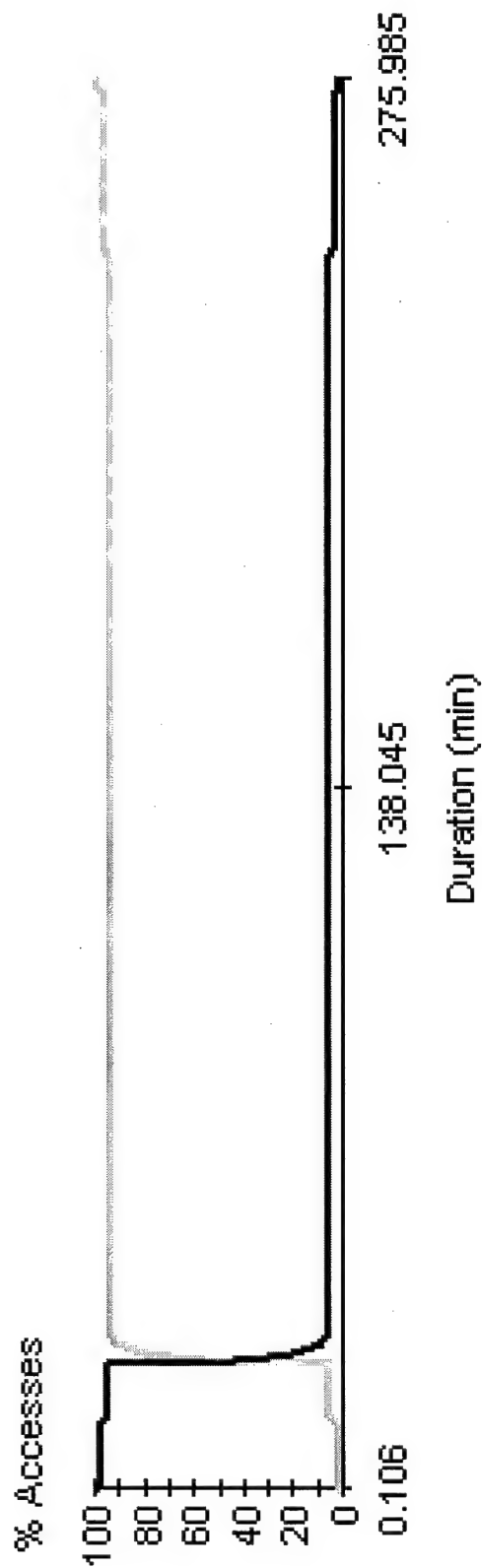
— % Target Area under gap time

Figure B1

Total Number Satellites = 6
Planes = 2
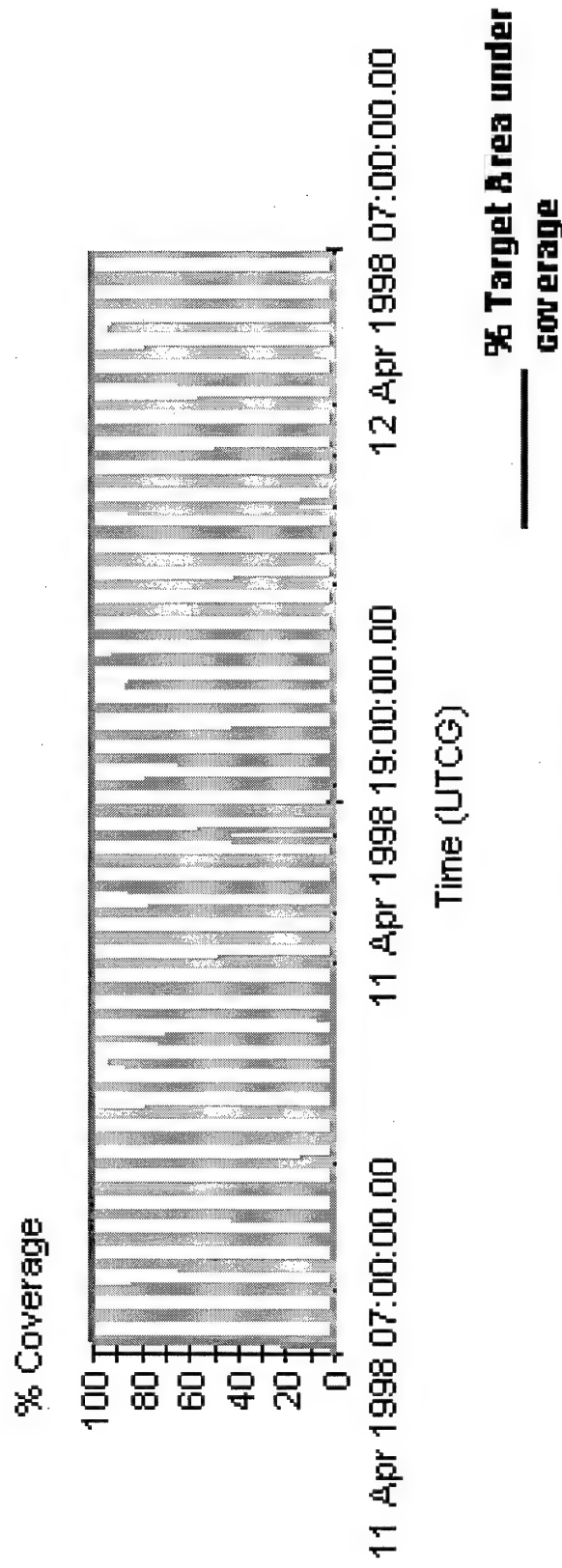Satellites Per Plane = 3
i = 40°
H = 500 km

58

Instant Coverage

% Coverage

100 80 60 40 20 0

3 Apr 1998 07:00:00.00   3 Apr 1998 19:00:00.00   4 Apr 1998 07:00:00.00

Time (UTCG)

—— % Target Area under coverage

Figure B2

Total Number Satellites = 6
Planes = 2
Satellites Per Plane = 3
i = 40°
H = 500 km

59

Gap Time

% Accesses

100 — 80 — 60 — 40 — 20 — 0

5.088   87.056   169.024

Duration (min)

—————— % Target Area under gap time
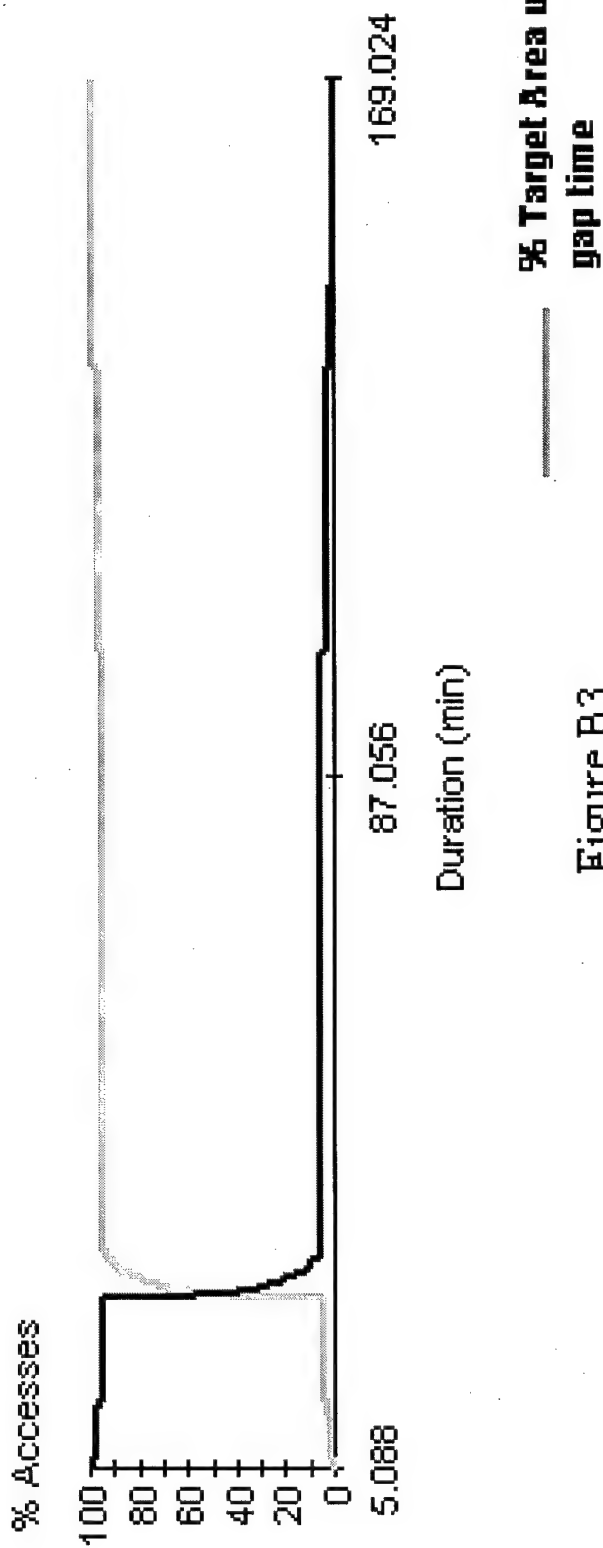
Figure B3

Total Number Satellites = 6
Planes = 2
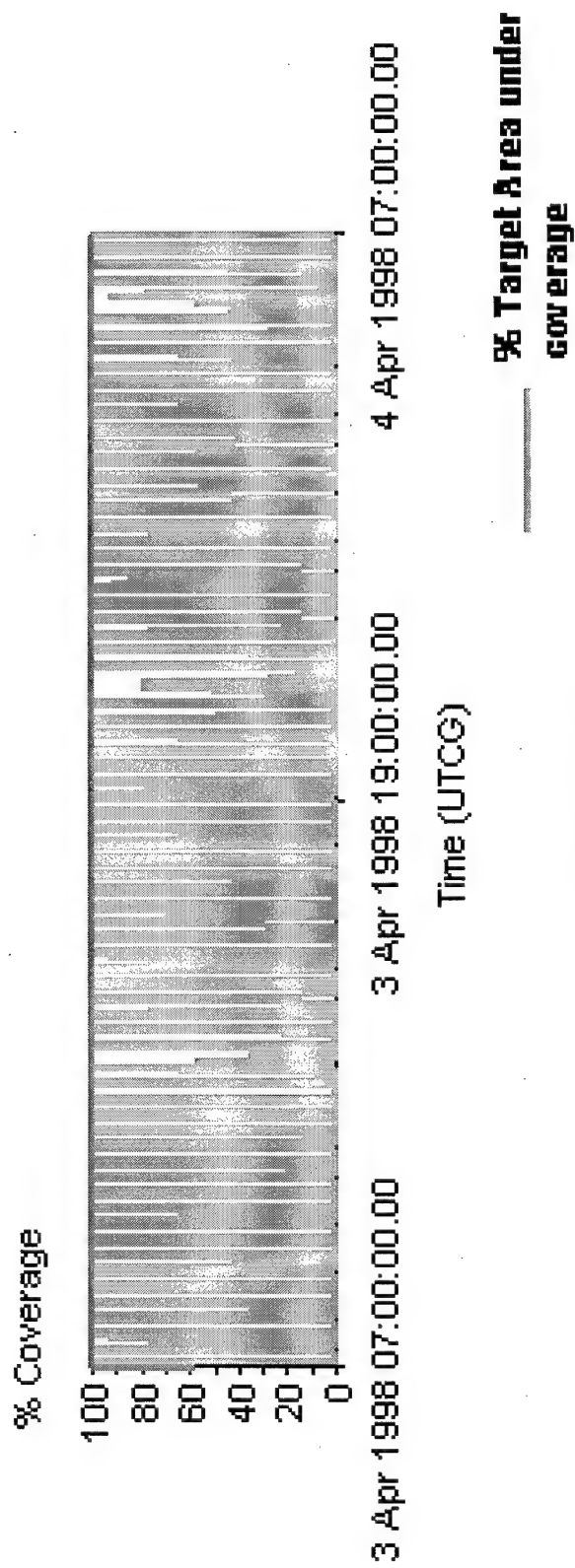Satellites Per Plane = 3
$i = 20°$
$H = 500$ km

Instant Coverage

% Coverage

100 80 60 40 20 0

3 Apr 1998 07:00:00.00   3 Apr 1998 19:00:00.00   4 Apr 1998 07:00:00.00

Time (UTCG)

——— % Target Area under coverage
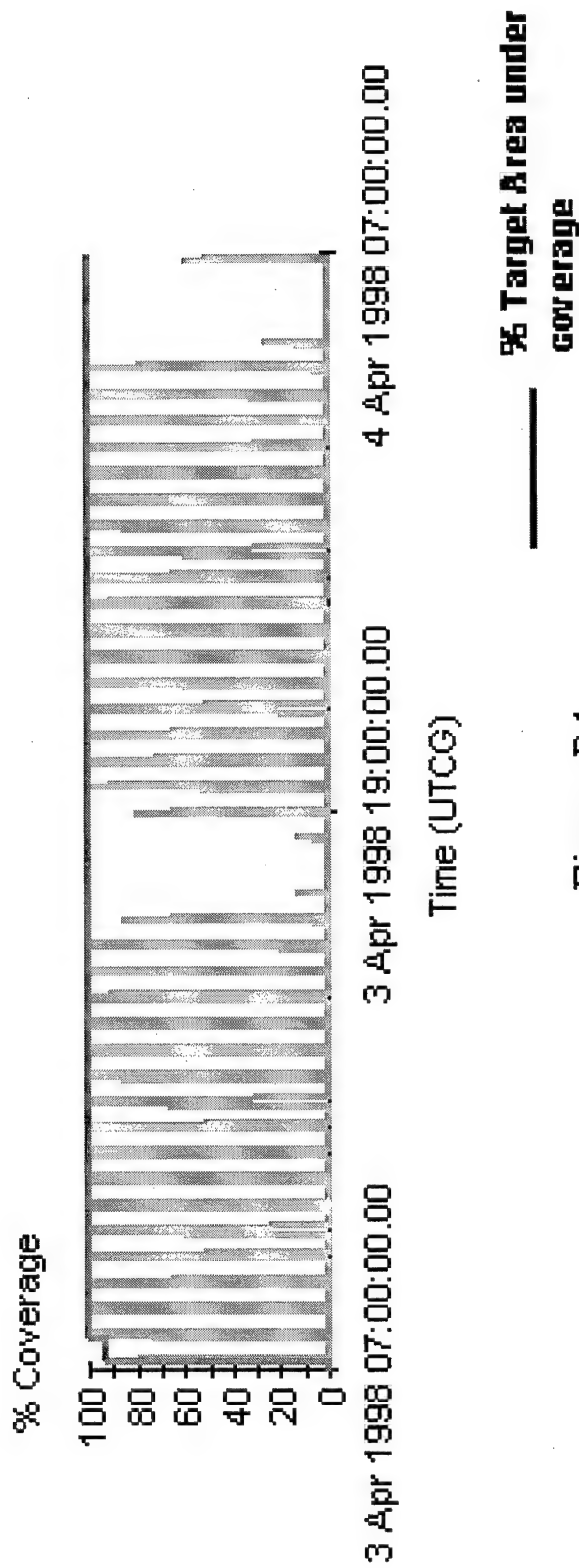
Figure B4

Total Number Satellites = 6
Planes = 2
Satellites Per Plane = 3
i = 20°
H = 500 km

Gap Time

% Accesses

100 —
80 —
60 —
40 —
20 —
0 —

14.722   37.208   59.694

Duration (min)

—— % Target Area under
gap time
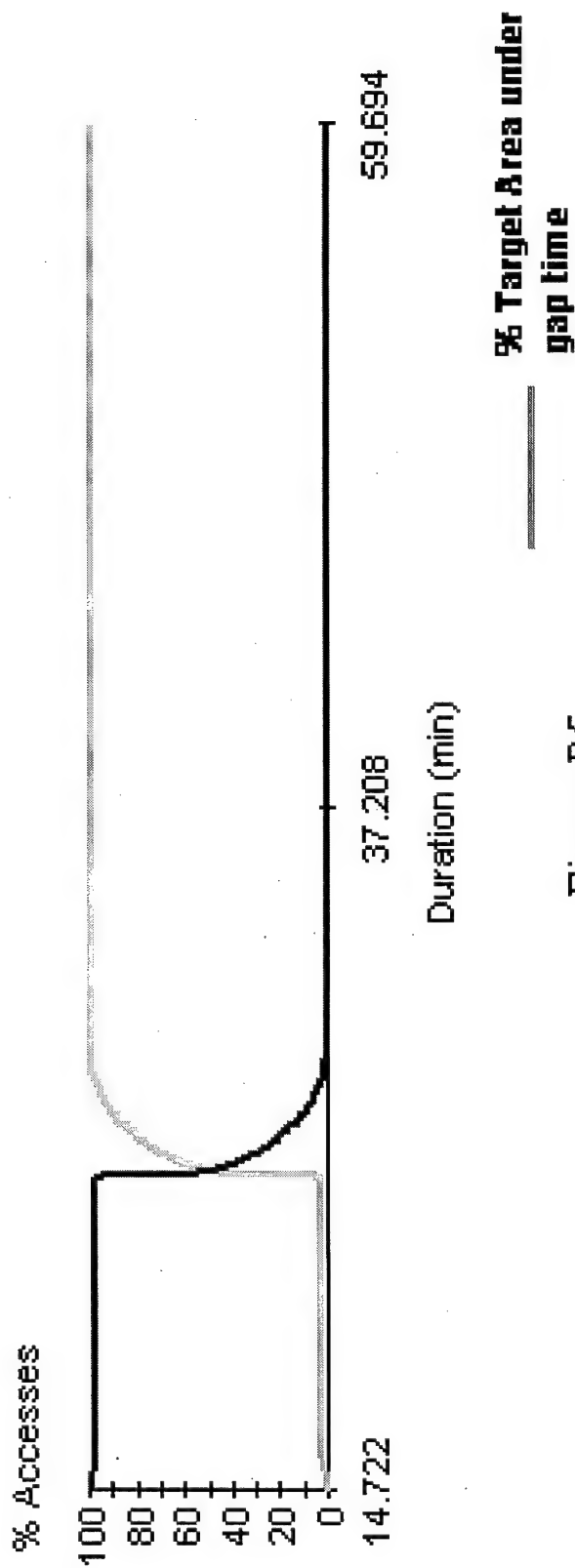
Figure B5

Total Number Satellites = 9
Planes = 3
Satellites Per Plane = 3
i = 40°
H = 500 km

62

Instant Coverage

% Coverage

Time (UTCG)

% Target Area under coverage

Figure B6

Total Number Satellites = 9
Planes = 3
Satellites Per Plane = 3
i = 40°
H = 500 km

63

Gap Time

% Accesses

100
80
60
40
20
0

0.076   13.276   26.475

Duration (min)

——— % Target Area under gap time
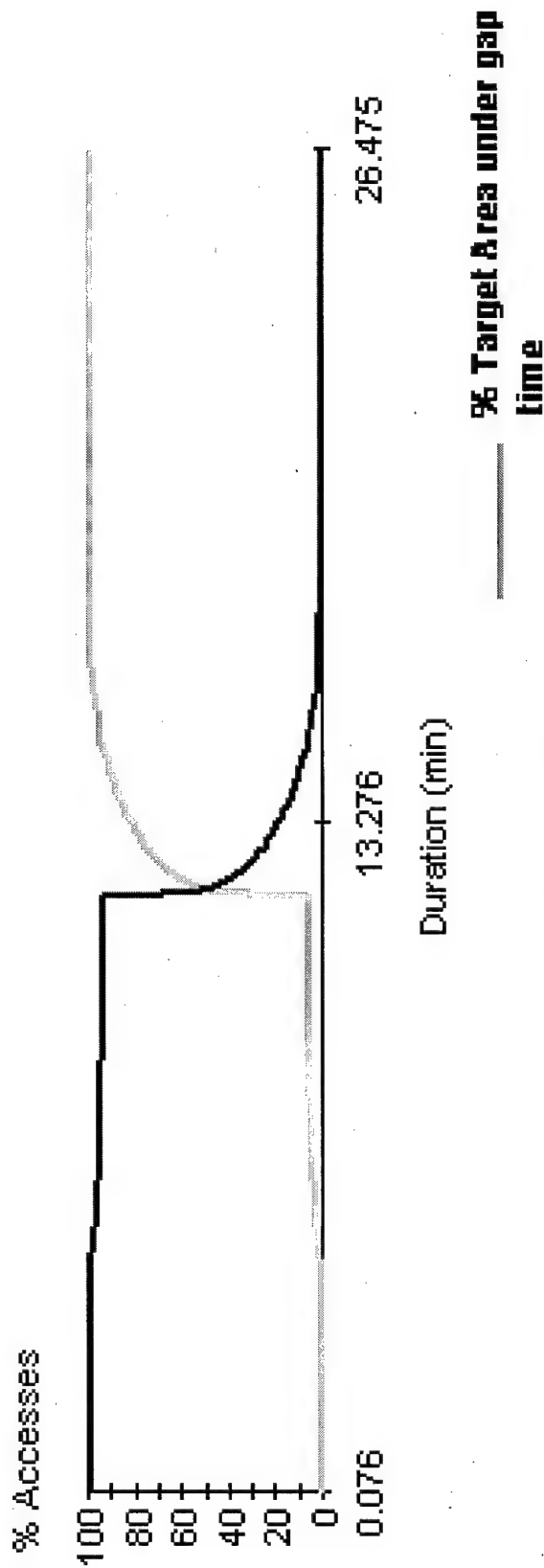
Figure B7

Total Number Satellites = 15
Planes = 3
Satellites Per Plane = 5
i = 40°
H = 500 km

64

Instant Coverage

% Coverage

100
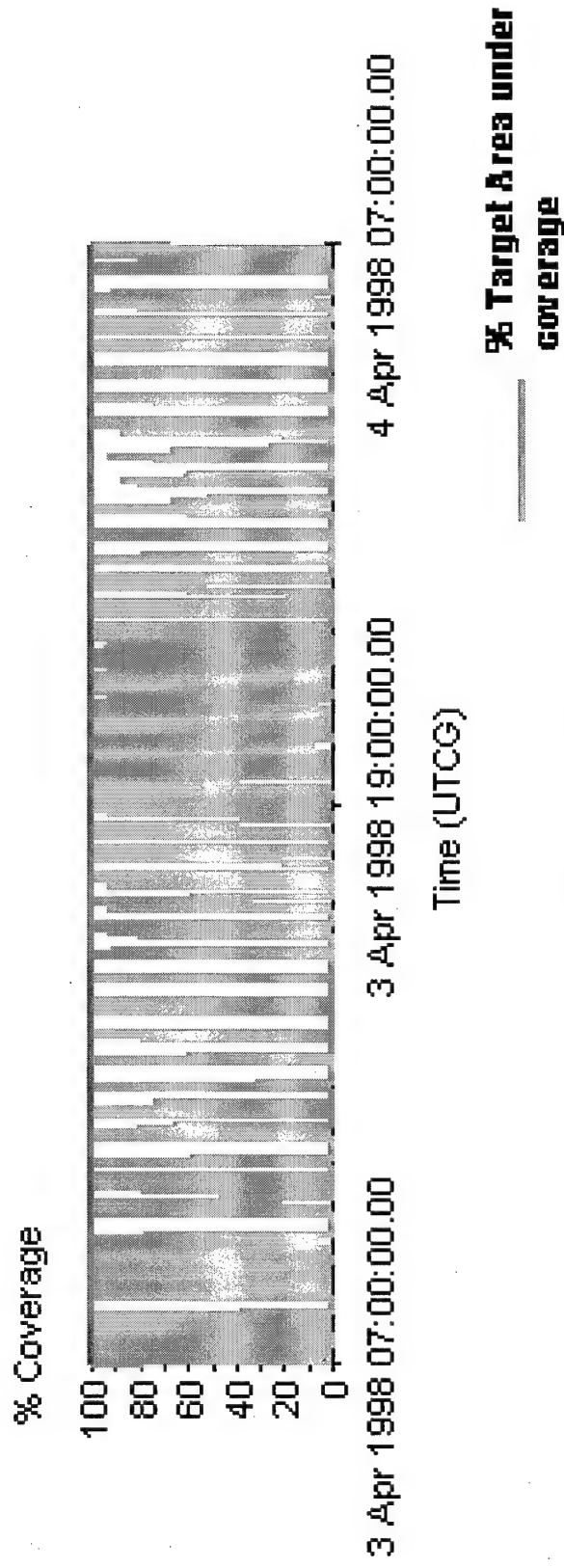80
60
40
20
0

3 Apr 1998 07:00:00.00   3 Apr 1998 19:00:00.00   4 Apr 1998 07:00:00.00

Time (UTCG)

—— % Target Area under
coverage

Figure B8

Total Number Satellites = 15
Planes = 3
Satellites Per Plane = 5
i = 40°
H = 500 km

Gap Time

% Accesses

100 —
80 —
60 —
40 —
20 —
0 —

1.417   15.676   29.934

Duration (min)

——— % Target Area under gap time
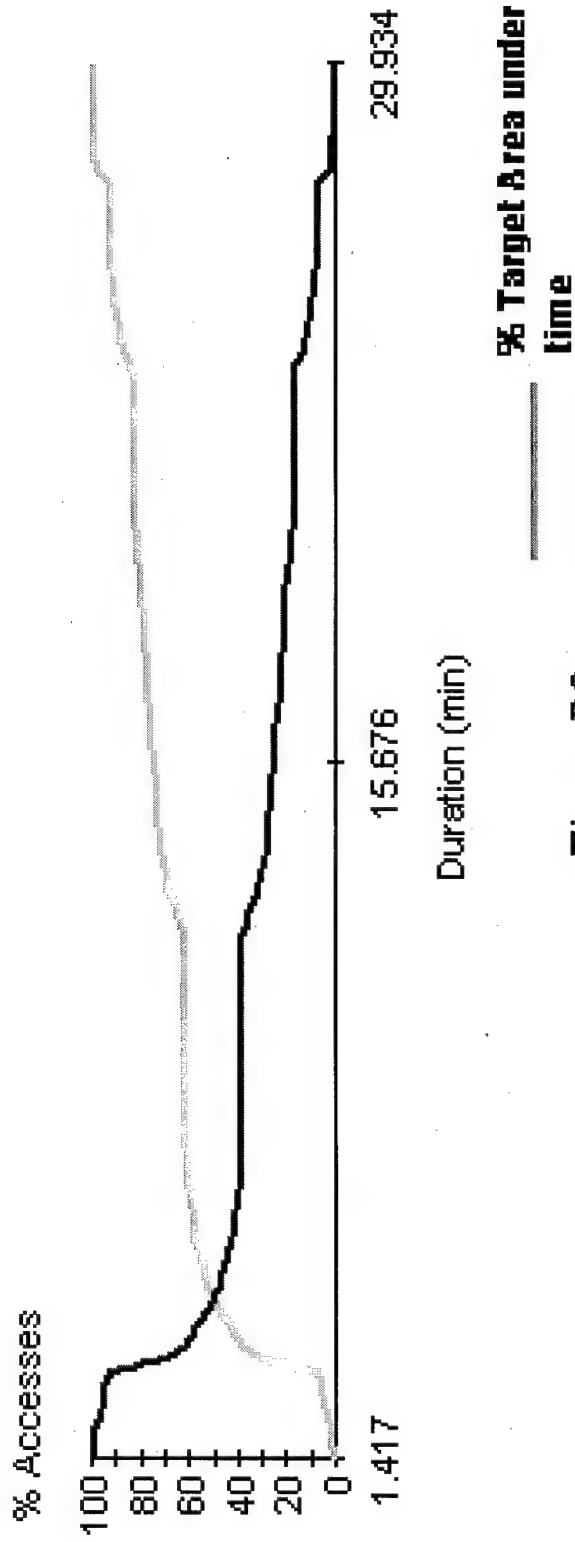
Figure B9

Total Number Satellites = 18
Planes = 6
Satellites Per Plane = 3
i = 40°
H = 500 km

66

Instant Coverage

% Coverage

Time (UTCG)

Figure B10

Total Number Satellites = 18
Planes = 6
Satellites Per Plane = 3
i = 40°
H = 500 km

APPENDIX C
FIGURES FOR PLANE CHANGE ANALYSIS

Delta V vs Inclination
Delta LAN (120 deg)
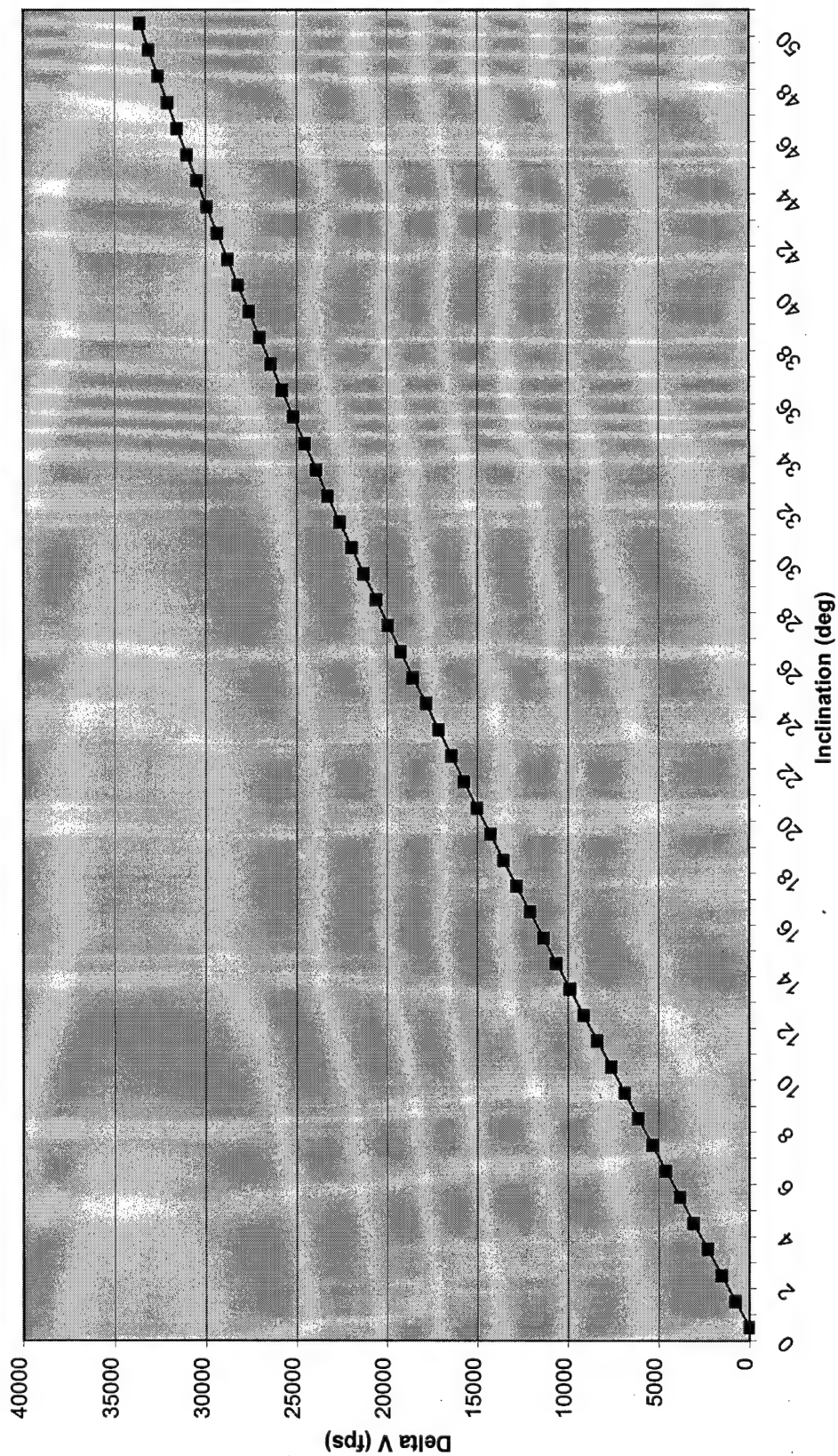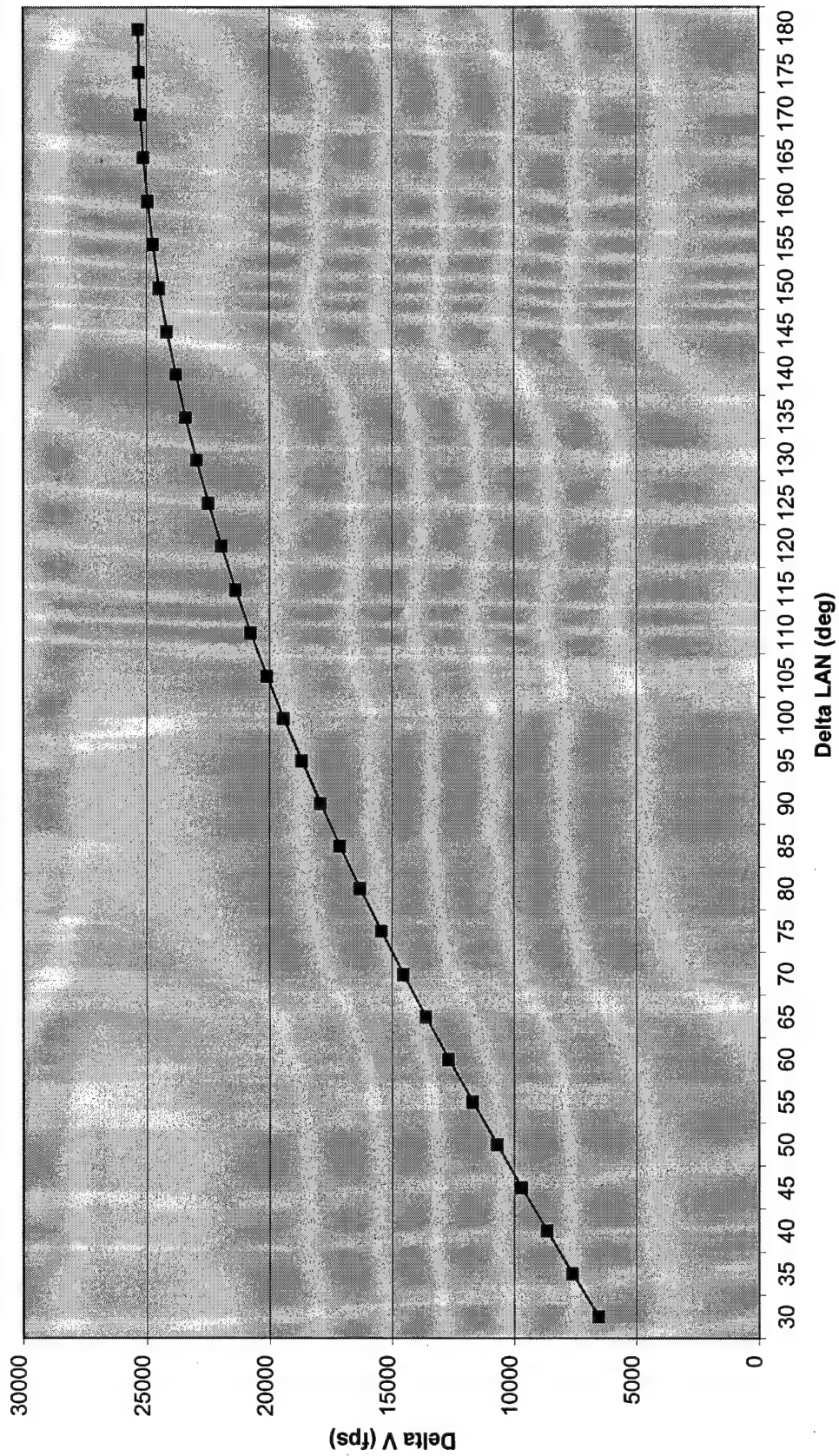
Figure C1

Delta V vs Delta LAN
Inclination = 30 deg

Figure C2

70

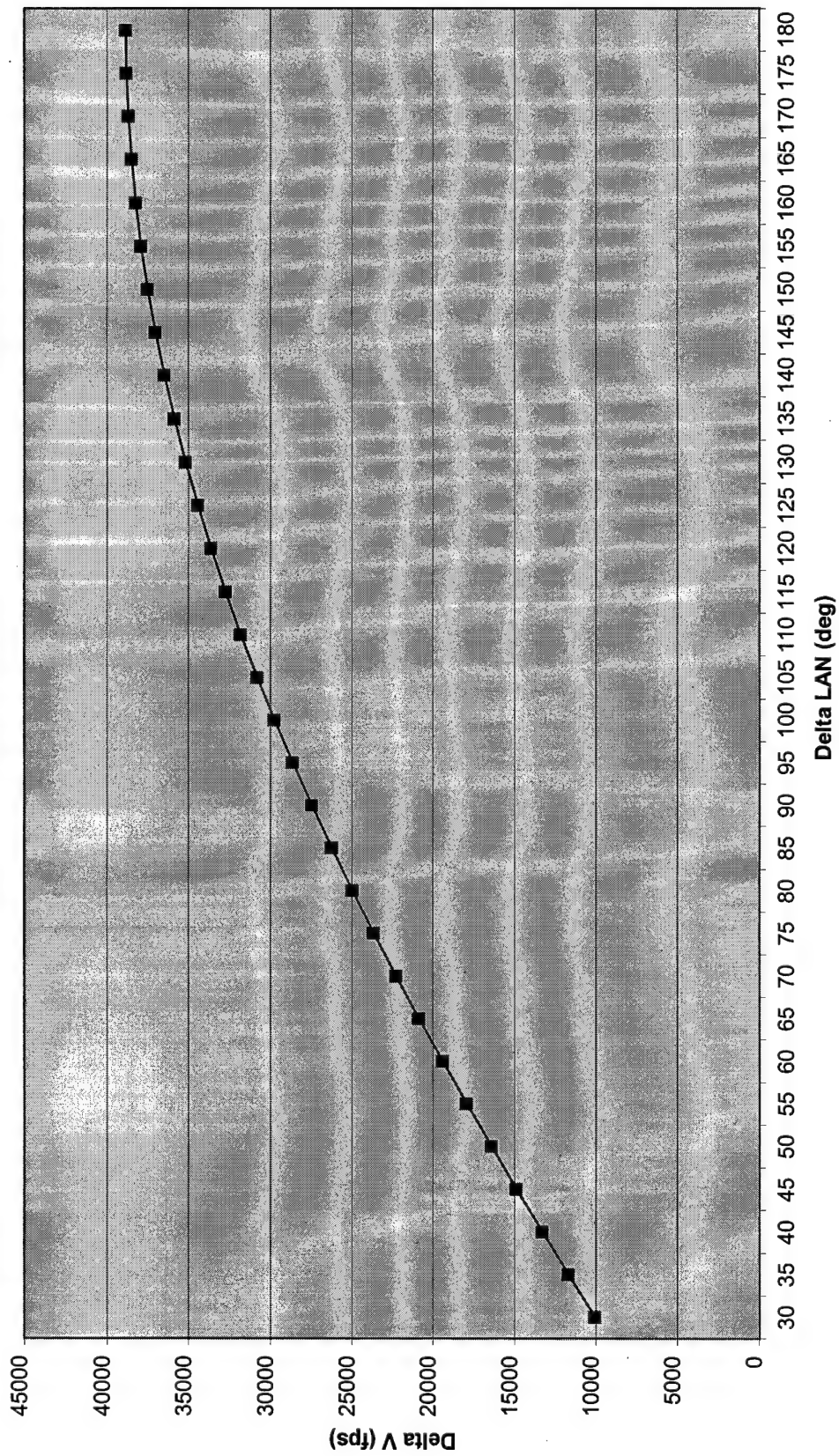**Delta V vs Delta LAN**
Inclination = 50 deg

Figure C3
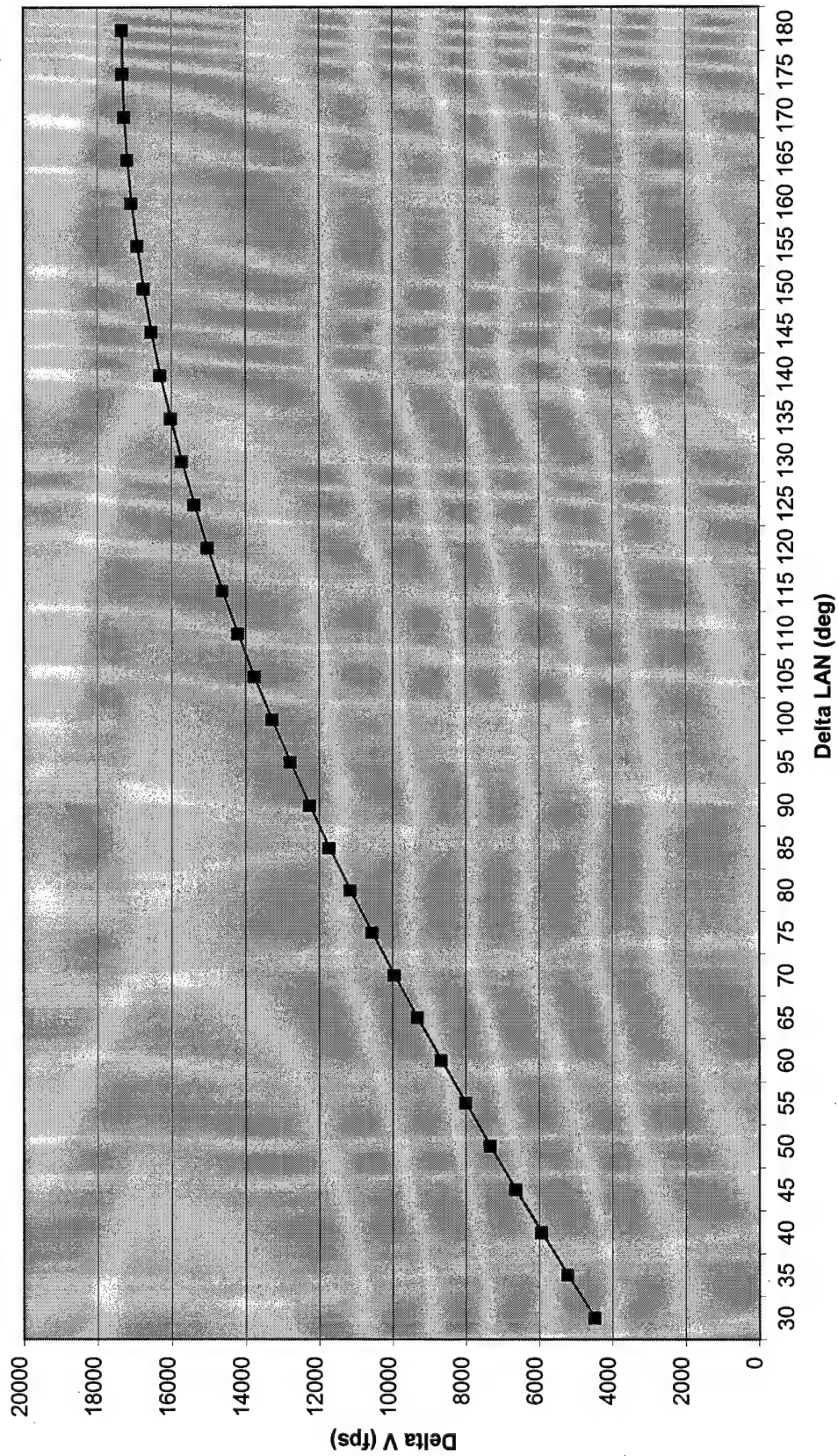
71

Delta V vs Delta LAN
Inclination = 20 deg

Figure C4

72

APPENDIX D
NEED FOR A MILITARY SPACE PLANE

The political climate of the world has changed drastically in the past decade. The problem and uncertainty of the future no longer involves a long and drawn out struggle between superpowers. It is about a single superpower, the United States, and many small independent nations. [9]. Many of these small nations are rogue nations, some no longer dependent on the financial and military aid of a superpower. Once operating on their own, possibilities exist for increased confrontation. The reasons for these confrontations are obviously numerous, complex, and can date back hundreds of years potentially involving much human emotion. It is foreseeable that under certain circumstances leaders may adopt aggressive behaviors without fully considering their consequences. This environment of potentially unstable countries and of uncertain future events has and will continue to dictate and shape the U.S. defensive operating environment for perhaps the next thirty years. More importantly, the proliferation and rapid advance of technology and information availability have made it very possible that certain nations gain access to weapons and capabilities of considerable destructive power, speed, and range [9]. Many currently have or will have access to nuclear weapons of mass destruction. The threat this poses to the U.S. and its allies goes without saying.

Though many nations of concern do not have a strong space infrastructure, many can or may have the capability to destroy the U.S. space infrastructure. [10]. For example, imagine a scenario where the U.S. enters into another confrontation with Iraq. In this case Iraq has no real access to space infrastructure, but it does have the ability to launch scud missile such that they detonate in the lower atmosphere. If Iraq were to place a nuclear weapon on a scud and detonate it in the lower atmosphere, the electromagnetic pulse could disable U.S. satellites orbiting in Low Earth Orbit. A

potential result of this kind of attack is that much of our C3 capability may be wiped out. The bottom line is that nuclear weapons do not need to be accurate in order to be effective in wiping out U.S. global vision [10].

Within the next few years, the U.S. most likely will not be able to guard against this kind of attack, at least in preventing satellites from being damaged by nuclear weapons. If satellites are lost, U.S. dependence on such systems could be crippling. It is possible to respond to such an attack by establishing and creating procedures for rapid replenishment or reconstitution of lost or disabled space assets. Rapid reconstitution of military systems is important in order to be successful [11]. The other threats against U.S. space assets include the following: [5]

1. Counter Space Forces: Kinetic and physical weapons of destruction
2. Espionage: Information collection
3. Sabotage: Attempts to hinder production, transportation, distribution of assets
4. Electronic Warfare: Jam communication routes
5. Nuclear Forces: Using nuclear weapons to disable or destroy satellites

In addition to these threats the U.S. does not currently have the ability to counter the following threats: [3].

1. Orbital: Where a potential adversary has space assets that are in orbit which can provide and maintain intelligence and identification on U.S. space based systems and even perform counter space missions against the U.S.
2. Terrestrial: Where a potential adversary has space assets that are in orbit and can provide and maintain intelligence and identification of U.S. ground forces and movements.

As part of its new policy for engaging and dealing with potential threats, the U.S. has three broad missions. First, the U.S. can and will deliver accurate, lethal blows before or at the onset of hostilities. Second, the U.S. must sustain its fighting abilities without huge support infrastructures and deployed forces. Third, the U.S. will provide routine,

reliable, flexible access to space [9]. It is this third point that hints at the ever-increasing

reliability on space by the U.S. and its military. There are many reasons for the increased

use and reliance on space by the U.S. Some examples of these reasons are included in the

list below. [5]

1. Rapid advances taking place in communication technologies and an increase on space based communications infrastructure.
2. Military drawdown and the cost and threat of maintaining deployed forces.
3. Increased access to space through maturing launch technologies and increased expansion and interest by commercial and civilian organizations.
4. The global view that is inherent in space based systems.
5. Aircraft do not possess the range, altitude and speed necessary to operate in exo-atmospheric and worldwide missions.
6. Aircraft do not have the speed necessary to hold targets at risk in a timely manner.
7. Aircraft do not have the range or endurance to provide worldwide coverage
8. Aircraft will become more vulnerable against improving enemy defenses.

The characteristic of space that is of primary importance to the military is its

vantage of view. It is this very characteristic that has been exploited for the past four

decades with artificial satellites and was one of the primary uses of aircraft in World War

I [11]. Vantage of view, or more appropriately, global view, provides and allows for

some if not all of the following characteristics: near-continuous and near-real time

surveillance, reconnaissance, exploration, environmental sensing, information collection,

research, intelligence, navigation, and command, control, and communication [11]. For

the purposes of the military, global view makes it possible to know about enemy forces

for most if not all of the time, expanding the capability to make critical decisions in the

time of heightened hostility. Moreover, the simple fact that potential adversaries know

that the U.S. has near-constant, near-real time information about their actions and

movements is in itself a potential deterrent to hostile action [11]. More importantly,

global view can act as a virtual forward presence without the costly deployment of U.S.

troops while still providing deterrent effects. With space assets, the U.S. can collect and distribute information rapidly, potentially increasing both national and international security [11].

The United States recognizes all the above mentioned threats and limitations and has drawn up policies and procedures that will hopefully eliminate or minimize them. For example, the 19 September 1996 National Space Policy calls for the defense and intelligence related activities in space that will ensure the defense of the U.S. and its assets [3]. Under this policy, the DoD will maintain the ability to execute missions of Space Support, Space Control, Force Enhancement, and Force Application. Elements of the national and military strategy include "strategic deterrence and defense, forward presence, crisis response, and reconstitution." [5]. In order to be able to provide all of these, the U.S. will need reliable, rapid access to space. With such capability, the U.S. will be able to deploy space based assets that can deter aggression without deploying U.S ground forces [3].

The question then is, how can the military, DoD, and commercial and civil organizations provide rapid, cheap, and reliable access to space? In October 1996, the Air Force Executive Guidance stated that the Air Force will maintain the Military Space Plane capability for rapid global precision strike. This same space plane capability can also be used for rapid space lift [3]. With such a trans-atmospheric vehicle, satellites could be replaced quickly in comparison with today's launch systems. Up to now, the problem with space launch is that it has been extremely expensive, and the turn around time will not support the missions that are required and being described here. Until this problem can be resolved, other technologies can be used but they be limiting in terms of

the goals they will achieve. "Inexpensive space lift is the enabling element which makes other aspects a reality." [11]. Without space lift, the U.S. may not realize the full benefits of global view.

APPENDIX E
MILITARY SPACE PLANE SYSTEM COMPARISON

JSTARS is a modified Boeing 707 that carries a radar antenna. The radar is used to identify and locate ground targets in all kinds of weather conditions, similar to the MSP/SMV/TACSAT system [8]. It can do this because the radar frequency is not as susceptible to atmospheric absorption as other frequencies such as visible light and infrared energy. The JSTARS has several radar modes of operation. Within these modes it can provide wide area surveillance with a wide radar beam, or it can narrow the beam and raise the resolution to focus in on particular targets [8]. In terms of its endurance and capability, JSTARS can generally see targets as far as 200 km away and can stay aloft for about 11 hours without refueling [8].

So how does the MSP/SMV/TACSAT system compare with JSTARS? In terms of endurance, the MSP system is superior. It can provide coverage for an indefinite amount of time or for about as long as it would be needed. Additionally, it can be tailored to provide different types of coverage. The gap times in particular can be directly specified and varying resolutions can be achieved depending on the type of sensor that is included with the TACSAT payload. It should be noted that the analysis done here does not attempt to take into account sensor types on board the spacecraft. What the analysis does show is the satellite's potential instantaneous access area given a 10° elevation mask, or for the case of a 500 km orbit, a 65.96° nadir angle. Whether or not the satellite is capable of using this access area depends on the sensor equipment it employs. If the satellite uses a steerable radar antenna, it will most likely be capable of utilizing the complete instantaneous access area, in all weather conditions. Given this, the MSP system will be capable of outperforming JSTARS in both coverage and endurance.

On the flip side, time to deployment may still lie in favor of JSTARS. For the MSP system, getting a satellite constellation deployed within 16 hours requires a lot of things to go right, leaving room for several things to potentially go wrong. JSTARS on the other hand can deploy to a critical location within 16 hours and its operations are established and proven. So the answer as to which system is better depends largely on the criticality of the situation, its potential duration, as well as what the overall mission is in general.

As a final note on the comparison of these two systems, the one major advantage of the MSP system over JSTARS is altitude. Since the MSP system is in orbit above the earth, it will be more likely to avoid future enemy defense systems. Additionally, since the satellites are autonomous systems, there is no risk of loss of life. In the future JSTARS simply will not be able to defend itself as well as the MSP system in terms of both altitude and speed.

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